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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-

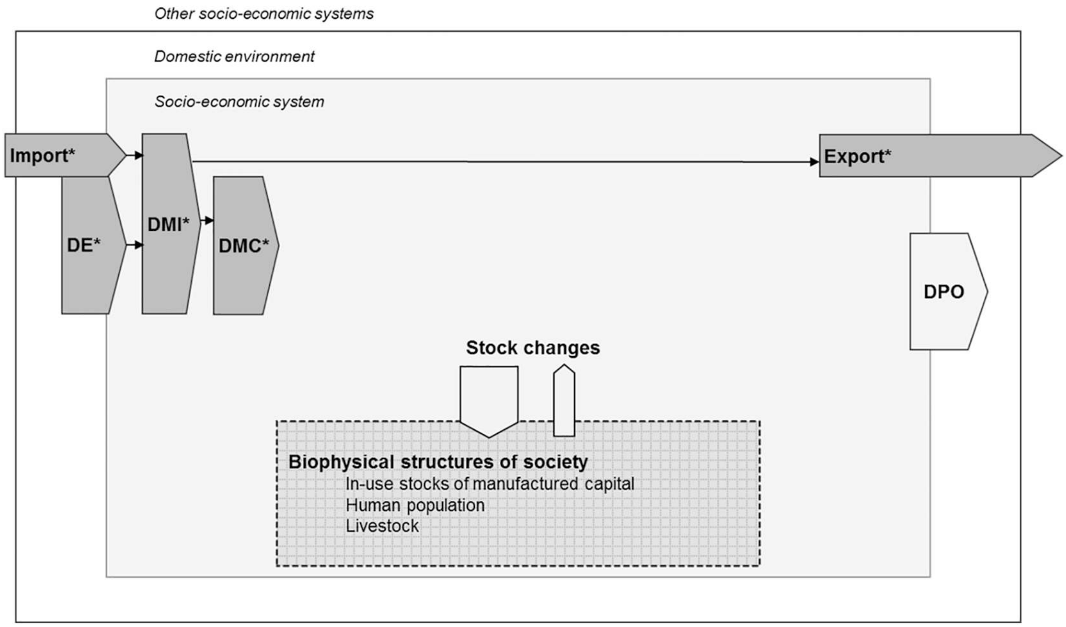

Fig. 1. The framework of economy-wide material flow accounting, adapted from (Eurostat, 2001; Fischer-Kowalski et al., 2011; OECD, 2008). Conceptually, all socio-economic material flows are included to achieve mass balancing at the level of the socio-economic system, starting from 'inputs' covering domestic extraction (DE) and import, to all 'outputs', including exports and all domestic processed outputs (DPO) of waste and emissions. Derived headline indicators are the domestic material inputs (DMI) and domestic material consumption (DMC). However, empirical application is still partial (indicated with an asterix) and in-use stocks, their dynamics and all domestic processed outputs are not systematically measured yet.

Martin, 2014; Giljum and Hubacek, 2004) and monetary (Eisenmenger et al., 2016; Malik et al., 2018; Wiedmann et al., 2015) input-output tables to open this black box, linking resource use with production and consumption along (monetary) inter-sectoral relationships. However, so far input-output based approaches also suffer from an incomplete treatment of in-use stocks of capital and their dynamics and a fully mass-balanced treatment of all waste and recycling resulting from economy-wide resource use has only been achieved for specific cases and materials (Majeau-Bettez et al., 2016; Nakamura and Kondo, 2009; Pauliuk et al., 2015; Pauliuk and Müller, 2014; Tisserant et al., 2017). Ew-MFA research efforts meanwhile focused on developing and implementing the comprehensive accounting methods across many different material flows and the derived indicators shown in (Fig. 1), providing consistent time-series for all countries of the world (Krausmann et al., 2017a; Schandl et al., 2017).

In current practice, ew-MFA databases cover domestic extraction of primary materials, biophysical imports and exports, as well as derived indicators (Fig. 1, linked flows marked with an asterisk). Economy-wide material flows are classified into 45–50 material categories at the most detailed level. These categories are usually presented at an aggregated level of four major categories: biomass, metal ores, fossil energy carriers, and non-metallic minerals. The mass-balanced indicators of Domestic Material Consumption (DMC = Domestic Extraction + Imports − Exports) and Domestic Material Inputs (DMI = Domestic Extraction + Imports) are routinely reported for nearly all countries of the world and are widely used in policy and research (Krausmann et al., 2017a; Schandl et al., 2017). Several international datasets with global coverage have been compiled, with time series data from 1950 (Schaffartzik et al., 2014), 1980 (Giljum et al., 2014), and globally also for the entire 20th century (Krausmann et al., 2018, 2009). Recently, an internationally harmonized dataset for 1970–2013 (including forecasting until 2017) has been jointly compiled by the afore mentioned research teams under the umbrella of UNEP (Schandl et al., 2017; UNEP, 2016). This data can be freely accessed at http://www.resourcepanel.org/reports/assessing-global-resource-use and is subject to regular updating and reporting by UNEP.

While flows related to the in-use stock (gross & net additions to stock) as well as outflows from the socio-economic system (the Domestic Processed Output to nature [DPO] indicator) are conceptually included in the framework (Fig. 1, light grey boxes), they have so far been addressed less frequently, due to lack of consistent data (Fischer-Kowalski et al., 2011; Krausmann et al., 2017a). Consequently, stock-related flows were mainly estimated as a net mass-balance between inputs and outputs, suggesting full systems closure but actually absorbing any inconsistencies and uncertainties. As a consequence, indicators and accounting methods for output flows are both less elaborated and not standardized (Eurostat, 2001; Fischer-Kowalski et al., 2011; Kovanda, 2017; Kovanda et al., 2007; OECD, 2008).

To further advance the ew-MFA framework, two major obstacles need to be overcome. Firstly, a detailed analysis of each material or substance and their transformations in the socioeconomic system seems prohibitively time-consuming within a standardized economy-wide approach, because currently no comprehensive data sources on primary and secondary resource use throughout the socioeconomic system exist. Recent research utilizing the general approach of material flow analysis methods has instead focused on the quantification of case-specific processes, end-uses, materials, and substances at various scales (Augiseau and Barles, 2016; Chen and Graedel, 2012; Müller et al., 2014a; Tanikawa et al., 2015). However, a simplified and easily transferable approach to cover all materials and whole economies across space and time is necessary.

Secondly, there is a general lack of comprehensive information on in-use stocks of manufactured capital and the related physical flows (Augiseau and Barles, 2016; Müller et al., 2014a; Tanikawa et al., 2015; Weisz et al., 2015). Under the umbrella of dynamic material flow analysis, different modelling approaches have been developed to investigate in-use stocks at different scales and with varying comprehensiveness and scopes (see next section). Until now, in ew-MFA in-use stocks were not directly estimated. Rather, gross additions to and removals from stocks are estimated as a material balance between apparent consumption of materials and information on outflows sourced from waste statistics – which has a range of limitations ('stock changes' in Fig. 1). While such a mass-balancing approach is a key conceptual principle of ew-MFA, in practice it suffers from the fragmentary nature of international waste statistics and its lack of consistency with ew-MFA system boundaries (Moriguchi and Hashimoto, 2016; Tisserant et al., 2017). Such a flow-centered approach also does not provide direct insights into the composition and dynamics of in-use stocks themselves, which constitutes an important knowledge gap itself (Krausmann et al., 2017a; Pauliuk and Müller, 2014; Weisz et al., 2015). Against this background, the extended ew-MFA framework presented herein has to:

a) respect thermodynamics and mass-balance principles across physical stocks and flows,
b) build upon the harmonized definitions and conventions of ew-MFA,
c) quantify in-use stocks of manufactured capital and their temporal dynamics,
d) consistently quantify flows of secondary (re- or downcycled) materials in the socioeconomic system,
e) contribute to closing the knowledge gap in regards to domestic processed outputs to nature.

2.1. Choosing the appropriate stock modelling strategy for extending ew-MFA

Several reviews recently attempted to classify stock quantification approaches (Augiseau and Barles, 2016; Müller et al., 2014b; Tanikawa et al., 2015). There seems to be a general agreement that methods and models are either static or dynamic and that they are either top-down or bottom-up. However, considerable fuzziness on exact definitions remain, not least because many studies use hybrid approaches. In practice, available data and research objectives often leave little choice for method selection, regardless of the accuracy of the terms used to describe the model. Likewise, the objectives of the ew-MFA framework and the availability of its data call for a certain type of stock-flow model.

The information from ew-MFA on material consumption is derived and harmonized from production and trade statistics in a static manner. A given year's account is calculated independently from previous years, rather than dynamically as a function of the values from previous years. Static accounting methods have been utilized in stock modelling as well. However, compared to resource extraction and trade, statistical data on in-use material stocks are scarce, often of poor quality and often cannot be linked to its physical properties. Some studies overcame these limitations by utilizing inventories and surveys about goods, infrastructure or buildings and information about their constituent materials. This can be done in a static bottom-up fashion, such as (García-Torres et al., 2017; Reyna and Chester, 2014) who sum individual buildings to obtain the stock of cities. This is very data intensive and for most countries these data do not exist in sufficient quality; therefore very few attempts have been made to apply this approach at the national level (Tanikawa et al., 2015; Wiedenhofer et al., 2015). Some authors have also applied a static top-down approach: for example, (Ortlepp et al., 2015) disaggregated Germany's sum of floor space to various construction types, while (Rauch, 2009) spatially allocated shares of the national metal in-use stocks to areas, based on their local GDP. Both static approaches can produce high-resolution stock estimates, but their reliance on specific survey data and their static nature cannot assure that the entire material stock and all flows are accounted for. Indeed disparities between bottom-up and top-down accounts are reported (Schiller et al., 2017). Static stock accounting can be done even if inflow and outflow data are not available. However, this supposed advantage also hampers harmonization with information on physical inflows and outflows of waste (Augiseau and Barles, 2016; Müller et al., 2014b; Schiller et al., 2017; Tanikawa et al., 2015; Wiedenhofer et al., 2015), as is one of the goals herein. Based on these considerations, we find that static approaches are not that useful for the purposes sketched out in the previous sections.

Another modelling approach, System Dynamics, seems quite attractive because it incorporates flows, stocks, and their socio-economic drivers in a harmonized fashion. It can be used on multiple scales and incorporates feedbacks to unravel non-linear and chaotic system behaviour. Indeed, it was one of the earliest methods used to model country and global scale flows and stocks with the landmark “Limits to Growth” study (Meadows et al., 1972). System Dynamics stock-flow models for specific material markets like aluminum (Sverdrup et al., 2015), rare earths (Nguyen and Imholte, 2016) and copper (Glöser-Chahoud et al., 2016) have been developed. However, the requirement of a full understanding of relationships between its components complicates this approach. Efforts are ongoing to develop a fully functional national-level Systems Dynamics stocks and flows model for the Australian economy (Turner et al., 2011). However, the current level of data aggregation in ew-MFA and the treatment of the economy as a “black box” does not render the System Dynamics approach feasible yet, because too much necessary information is not yet available.

A more simplified version of such a modelling approach is termed ‘dynamic material flow analysis’, which incorporates time is an active model variable but does not incorporate feedback loops. Rather, dynamic MFA draws on the material balancing principle to complement missing data, be it flows or stocks, using sets of time-dependent material balance equations (Brunner and Rechberger, 2017; Müller, 2006; Müller et al., 2014b). Differentiating between top-down and bottom-up models is less trivial in dynamic MFA models but arguably also less meaningful. Rather, the significant difference is which variables are exogenous to the model (model input parameters, not to be confused with biophysical inflows) and which ones are endogenous, i.e. calculated by the model (model outputs). Of the three variables (inflows, stocks, and outflows), the model input parameters are either physical inflows or stocks, while the remaining two variables are then endogenously calculated. This distinction also suggests a more useful typology of modelling approaches: inflow-driven versus stock-driven models, respectively.

In stock-driven models as popularized by Müller (Müller, 2006), the stock is conceptualized as consisting of cohorts of service units which have specific material compositions, for example vehicles or buildings of differing age classes or cohorts. The development of these service units are exogenous to the model and are based on surveys or other statistical information. Because physical outflows are often not empirically known, each cohort has its own failure curve to estimate its outflows over time, or conversely, a survival or depreciation curve to estimate the remaining stock (Miatto et al., 2017a). The cohorts' outflows in a given year are summed as the total outflow. Inflows are endogenously calculated as the quantities required to maintain and expand the exogenously determined level of in-use stock. This enables not only to model the inflows that were required for historical stock levels, but also the creation of what-if scenarios, i.e., what future inflows would be required to obtain a certain stock level, given a specific survival curve. The exogenously given level of stock is often linked to an exogenously given “driver”, such as population or economic development and is thus sometimes referred to as demand-driven or activity-driven modelling. This approach has been employed to a range of issues, e.g. residential buildings (Heeren and Hellweg, 2018; Sandberg and Brattebø, 2012), vehicles (Cabrera Serrenho and Allwood, 2016), transport infrastructure (Yang and Kohler, 2008) and even sewage systems (Lwin et al., 2017). The specific stock-driven approach by (Müller, 2006) has substantial conceptual benefits by directly linking material stocks and flows with service units. However, modelling the entirety of all in-use stocks and flows for a certain material in a socioeconomic system using this approach requires data covering all the various end-uses and the related physical stocks and flows, making this a highly data intensive approach. Because of these reasons, stock-driven dynamic models as have rarely been applied to model economy-wide stocks at the national level. Most national to global applications so far, cover only certain fractions of in-use stocks (Augiseau and Barles, 2016; Müller et al., 2014b), or are only possible in countries which have long-standing research efforts dedicated to building such databases (Schiller et al., 2016; Tanikawa et al., 2015). Stock-driven approaches are therefore of limited use for the development of a comprehensive approach to integrating stock dynamics into ew-MFA which should be applicable and transferable to many countries and over longer time-periods.

Inflow-driven dynamic models on the other hand start with the physical inflows as exogenous model inputs, information that can be derived directly from existing ew-MFA and production statistics (Fishman et al., 2014; Krausmann et al., 2017b). This means that the cohorts, which are traced throughout the model, are the physical inflows into the stock in different time steps. The inflows then have an exogenously given service lifetime and depreciate over time, becoming physical outflows in the same fashion as in the stock-driven model. In this method, the stock is an endogenously calculated output of the model; it is the sum of all materials remaining in-use in the cohorts of past inflows. Inflow data can be along socioeconomic end-uses car sales, which are converted into mass of materials, which makes the account more sector-oriented (Cabrera Serrenho and Allwood, 2016). However, data can also be directly in terms of the mass of a material (e.g. steel or concrete) and the allocation to end-uses is either then be calculated within the model or not be calculated at all, treating the in-use phase as a “black box”. Such a simplification adds flexibility to the types of material flows and stocks that can be modelled; ranging from fabricated products in various end-uses and scales such as steel (Daigo et al., 2007), construction materials (Fishman et al., 2014; Krausmann et al., 2017b), carbon in socioeconomic in-use stocks (Lauk et al., 2012), to more specific issues such as carbon nanotubes (Bornhöft et al., 2016). Such an inflow-driven approach also enables a what-if scenario design. In this case, it explores the size of stocks as consequences of exogenously given scenario assumptions about inflows and survival curves. The inflow-driven model is therefore a compelling choice for the ew-MFA framework, which reports flows at the material or even substance level (e.g. concrete or steel) rather than the goods and end-uses that are composed of these materials (e.g. I-beams, buildings, or cars), and the specifics of end-uses are not a prerequisite – however they constitute an important next step. This approach also lends itself well to the highly aggregated character of ew-MFA, whose derived indicators are often reported alongside other aggregate socioeconomic information such as GDP.

2.2. The Dynamic Material Inputs, Stocks and Outputs (MISO) Model

In the following, we utilize the ‘overview, design principles and details’ (ODD) protocol adapted for dynamic MFA (Müller et al., 2014a) (elements of the ODD are in bold). Due to space limitations, further details on the data, sources, equations and specific procedures applied, can be found in the SI 1.

Overview (MISO-model v1): The **purpose** of the model is to extend the ew-MFA framework by tracing the accumulation of processed stock-building materials as in-use stocks of manufactured capital and quantifying all processing, construction, and end-of-life wastes subsequently available for recycling. This requires a shift from differentiating materials extraction and trade by their material properties, as is common in ew-MFA, towards also characterizing key processing steps and major uses. We utilize a two-step procedure, where we firstly apply material flow accounting to characterize said uses, processes, occurring losses and waste, to quantify all stock-building material flows. In the second step, the model then handles primary and secondary stock-building materials and the occurring manufacturing & construction waste, within a dynamic inflow-driven **framework,** where annual cohorts or cohorts of in-use stocks are traced. By utilizing service lifetime distributions, end-of-life wastes from stocks are modelled, from which secondary materials are estimated based on recycling rates.

Exogenous model inputs are: primary stock-building materials; parameters on losses and wastes occurring in processing, re-manufacturing and construction; lifetime distributions; and recycling as well as down-cycling rates. **Endogenous model outputs** include: cohorts of in-use stocks; end-of-life waste; as well as recycled and down-cycled secondary material flows. We demonstrate our approach by tracing 16 of the 50 raw materials reported in ew-MFA (see Table S1 for details), which are processed into the following 14 stock-building **materials** (MISO-data v1.1, see SI).

- Biomass: solid wood and construction timber (1), paper and paperboard (2),
- Metals: iron and steel (3), copper (4), aluminum (5), all other metals (6),
- Fossil materials: plastics (7), bitumen and asphalt (8),
- Non-metallic minerals: cement and concrete (9), bricks (10), primary sand and gravel (11), down-cycled secondary construction minerals (12), flat glass (13) and container glass (14).

The first step of expanding the ew-MFA framework consists of allocating all material consumption to selected major uses and further to outputs of waste and emissions, in order to identify those material flows related to stock-building, which are then in the second step directly handled in the model. This means drastically simplifying the complexity of material and energy flows through socioeconomic systems and focusing on five key **stages or processes** in a first accounting step: materials processing of domestically consumed materials into *Energy use* and *material use*, *stock-building* and *waste management.* Please note that items in italic represent stages, processes and flows in the **systems overview** shown in Fig. 2. These stages are designed to be fully consistent and complementary to information and indicators from ew-MFA (items in grey, Fig. 2).

In the *materials processing* stage we summarize, simplify and quantify the entirety of all industrial activities in which primary raw materials and secondary recycled materials are transformed for further *material-*, *dissipative- and energy use*. Quantifying these flows is done via accounting of ew-MFA data and various additional industry statistics and literature sources (see SI), as well as combined information from accounting and modelling of secondary end-of-life materials (green items in Fig. 2). *Materials processing* covers the production of intermediate goods (e.g. processing wood harvest into pulp or industrial roundwood, smelting ores), as well as final products (steel bars for construction, burning of bricks, refining raw oil into fuels and plastics).

Energy uses of materials cover all food, feed as well as technical energy use, which are all ultimately subject to oxidation and catabolism (combustion and digestion), from which emissions to air and the production of liquid and solid waste necessarily result (Fig. 2). These transformations and quantities of resulting waste flows can be estimated from stoichiometric information, see Jacobi et al. (2018) and Krausmann et al. (2018) for further information. Most of these flows are subject to waste management in the broadest sense, e.g. ranging from treatment of municipal household waste, filtering of exhaust fumes, treatment of sewage, or in the future potentially even carbon capture and storage technologies.

Considerable *processing losses and waste* are also explicitly quantified, e.g. waste rock and slags from smelting of primary ores and secondary end-of-life metals, CO_2 from the calcination of limestone for cement production or water vapor losses during brick production (Fig. 2). Please note that, for example, the recycling of manufacturing scrap within industry is considered an internal flow of this aggregate processing step, as it remains within the manufacturing process; it is therefore not explicitly dealt with and subsumed within the mass-balance of this step. All processing losses and waste are subject to some form of waste management, see below.

Material uses include all products not used as energy carriers and are further subdivided into *dissipative uses*, *short-lived products* as well as *primary* and *secondary stock-building materials* (Fig. 2). *Dissipative uses* cover products such as fertilizer or salt for road maintenance in winter and are by definition directly linked into the aggregate ew-MFA

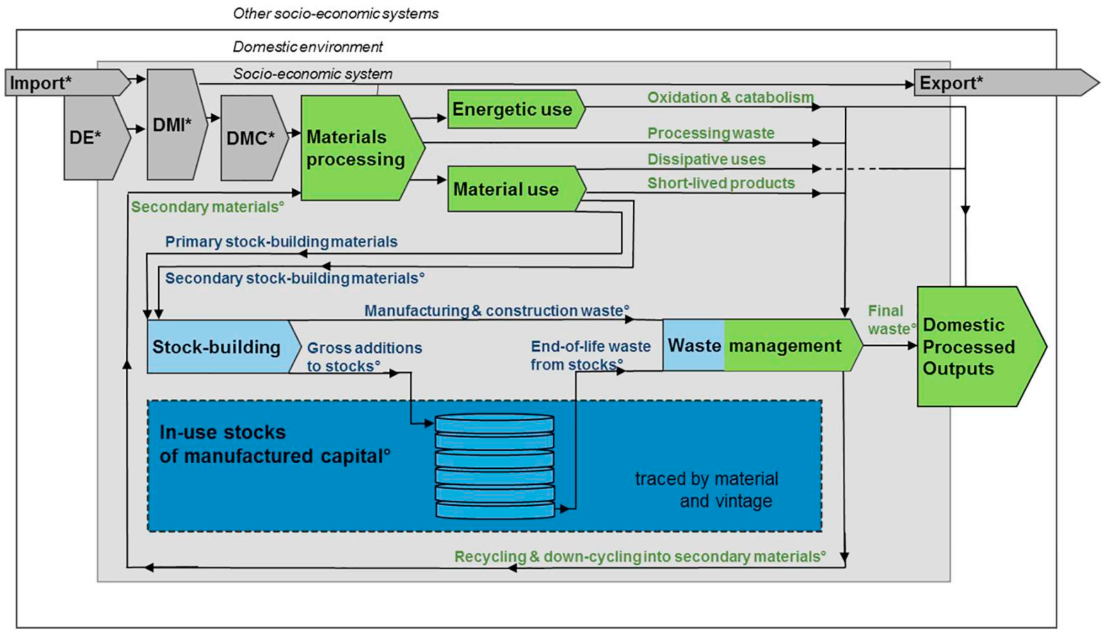

Fig. 2. System overview for the MISO-model as embedded into the extended ew-MFA approach. Items in grey indicate standardized indicators from ew-MFA. In the two-step procedure used for the MISO-modelling, green items represent extensions of the accounting principles, which then yield information for the dynamic input-driven model itself (in blue). Items marked with an asterix are regularly reported in ew-MFA databases. Primary stock-building materials are exogenous model inputs, as are parameters on manufacturing and construction waste, service lifetime distributions of in-use stocks and recycling rates (not shown). All items marked with ° are endogenous model outputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

indicator Domestic Processed Outputs (DPO) (Fig. 2). *Short-lived products* typically remain in-use for a period shorter than one year and are often discarded directly after use, e.g. newspapers, packaging, and hygiene articles. Finally, all *primary* and *secondary* recycled *stock-building materials* are identified and quantified (Fig. 2).

The *stock-building* stage is then handled directly in the dynamic MISO model, which constitutes the second part of the two-step procedure (blue items, Fig. 2). In this stage *primary and secondary stock-building materials* go through an aggregate construction and (re-)manufacturing process, where further losses and wastes can occur, while the majority of materials become biophysical *gross additions to stocks* in the form of annual cohorts of each material, e.g., as infrastructure, buildings, machinery or household goods (Fig. 2). Each cohort of in-use stock is then subject to its specific service lifetime distribution, which represents how long the specific stock-cohort remains in-use to provide services to society. These lifetime distributions also determine when the specific cohort turns into *end-of-life waste from stocks*.

Finally, in the **waste management** stage all physical flows from the two-step procedure mentioned above are bundled and handled (combination of blue and green in Fig. 2). We define this stage very broadly and include all[1] societal efforts in managing and treating solid and liquid waste as well as gaseous emissions. Therein we quantify waste for *recycling and downcycling into secondary materials* (Fig. 2, see SI for details and parameters), which are fed back into the *materials processing* stage. We define recycling as the re-use and re-manufacturing of end-of-life waste into the material of the same type and therefore it results in a similar range of products as the primary material allowed for (e.g. recycled steel, glass or paper). Downcycling covers materials that end up in applications, which allow only for a much smaller range of further uses (e.g. crushing bricks and concrete into secondary aggregates, which are used in the same manner as primary sand and gravel).

Materials that are not re- or downcycled are considered to be *final waste* and comprise both actually landfilled and uncontrolled waste, emissions into environmental media, e.g. from waste incineration or after filtering of exhausting fumes and hibernating stocks. Hibernating or 'lost' stocks are subject of ongoing research and cover all stocks which are not used anymore but usually remain in place without function and maintenance (e.g. abandoned buildings or other infrastructure, landfills) (Daigo et al., 2015; Hashimoto et al., 2009). Due to the lack of usable data on this issue, we treat these hibernating stocks as a final waste in the MISO-model v1. Nevertheless, it would be very interesting to quantify these hibernating stocks because they constitute a secondary resource deposit (Krook and Baas, 2013). All *final waste* is part of the ew-MFA indicator *domestic processed outputs* (DPO), which also includes gaseous emissions from oxidation of fossil fuels and biomass, human and animal excrements as well as dissipative uses of products.

The two-step approach of the MISO-model can be applied at any **spatial scale**; however, long-term ew-MFA data, usually longer than the longest service lifetimes used, as well as all further required exogenous model inputs, are usually only available on the national to the global scale (Supplementary Information 1 for details). In the example below, we investigate the global scale. The model is fully-consistent with **system boundaries** developed in ew-MFA in operationalizing the socioeconomic metabolism (Fischer-Kowalski et al., 2011; Fischer-Kowalski and Weisz, 1999). The **temporal extent** of the model application ranges from 1900 to 2014, based on a spin-up period from 1820 to 1900 and two exploratory scenarios from 2015 to 2050. The **temporal resolution** of the model is one year, which also yields the difference between short-lived products and in-use stocks – the latter are in-use for more than one year (e.g. newspapers versus furniture). Table 1 summarizes the **design concepts** used.

The key concept of dynamic material flow analysis and material flow accounting also used in the MISO-model is mass-balance, where all stock-building material flows *sbm*, manufacturing and construction waste *mcw*, gross additions to stock *GAS*, stock change ΔS and end-of-

[1] Conceptually also oxidation and catabolism yield waste flows of emissions and feces, which are subject to waste management in a broad sense (e.g. collection, filtering technology in tailpipes and factories, sewage treatment). However, we identified certain parts, where waste is not managed in any way and can directly be allocated to outputs to nature, for example respiration or the feces of free-range livestock. This is indicated in the flow from energy use to DPO in Fig. 2.

Table 1
Principles and concepts used for the MISO model, structured along the adapted ODD-protocol (Müller et al., 2014a).

Basic principles	Comprehensive perspective of economy-wide material flow accounting, mass-balances across all processes and for the entire system
Modelling approach (static, dynamic)	Inflow-driven dynamic stock modelling for cohorts/vintages and materials
Dissipation	Dissipative processes are explicitly deducted before the inflow-driven modelling traces cohorts of in-use stocks.
Spatial dimensions	Territorial system boundaries, mostly global to national, sub-national level is data limited, not spatially explicit.
Uncertainty	Parameter uncertainty from literature and assumed.
	Model output uncertainty quantified via Monte-Carlo Simulations.
	Validation of results against available literature and via mass-balances.
	Sensitivity assessments via several one-at-a-time tests and visual inspection of model behaviour.
	Global Sensitivity Analysis approach used to attribute model output uncertainty to model input parameters.

life waste from stock *EoL* within each year *t* have to be balanced (Eq. (1) and blue items in Fig. 2). Subsequently, mass-balance is also ensured over the entire temporal extent of the modelling, which means that all stock-building material inflows have to equal the in-use stock at the end of the modelling, minus the total of all manufacturing and construction as well as end-of-life waste, which occurred during the entire temporal extent of the modelling.

$$sbm_t - mcw_t = GAS_t = \Delta S_t - EoL\_waste\_stock_t \quad (1)$$

The second key concept is the use of service lifetime distributions, which are widely used to model the rate of demolition for each cohorts or vintages of in-use stock within a dynamic modelling framework (Augiseau and Barles, 2016; Fishman et al., 2014; Krausmann et al., 2017b; Miatto et al., 2017a; Müller et al., 2014a) (Eq. (2)). In this case, the in-use stock S of a given material at a time t is defined as the GAS remaining over the entire temporal extent τ, from the start of the modelling t_0 to the 'current' year t. This mathematical operation is a discreet convolution. The CDF is then the cumulative distribution function, yielding the probability that a cohort of material stock at the time t is still in-use (t - τ). In the model, different survival curves with different characteristics could be applied (Miatto et al. 2017), given enough information for parametrization. In the MISO-model v1, we use normal distributions, where μ is the mean lifetime and σ is the standard deviation of the lifetime distribution of each cohort.

$$S_t = \sum_{\tau=t_0}^{t} \left[GAS\ (\tau) \times \left(1 - \mathrm{CDF}\left(\frac{(t-\tau\ ) - \mu}{\sigma} \right) \right) \right] \quad (2)$$

Further **details** of the model ranging from fully documented equations along all materials, cohorts, time periods, to the implementation of the Monte-Carlo Simulations framework, the specific data sources, and a detailed documentation of our approach to sensitivity and uncertainty can be found in the supplementary information 1. Table S4 also contains an overview of the main exogenous model input parameters used to quantify the results shown in the following sections.

3. Stock-Flow Consistent Dynamics of the Global Socioeconomic Metabolism from 1900 to 2014

By applying the MISO-model extended ew-MFA framework, it is possible to analyse the joint dynamics of stocks and flows in the socioeconomic metabolism. We demonstrate these dynamics for the global scale from 1900 to 2014, by extending previous work which presented results until 2010 (Krausmann et al., 2017b). Additionally, herein also glass materials are now included in the modelling, which will yield slightly different results than in the previous study.

We find that materials processing, that is domestic extraction of primary resources and all end-of-life recycling flows, increased globally from 7.6 to 95.2 Gt/yr between 1900 and 2014, which is an annual 3.5% increase since 2010 alone (Fig. 3A). Secondary end-of-life recycled materials only make up 6% of all materials processing in 2014, indicating a continuously low degree of material loop closing (Fig. 3A). This corroborates results of a recent ew-MFA based assessment of the circularity of the global economy for 2005, which utilized only a simplified delay-model to estimate the amounts of end-of-life waste based on historical consumption of construction materials(Haas et al., 2015). The quantitatively most important use of processed materials has become stock-building, which increased from 1.2 to 49.8 Gt/yr, or from 16% to 53% of annual globally processed materials between 1900 and 2014 (Fig. 3B). Global in-use stocks of manufactured capital amounted to 928 Gt in 2014, a 26-fold increase since 1900 and an annual 3.9% increase since 2010 (Fig. 3C). Please note, that the inclusion of glass materials results in slightly higher stock estimates than in our previous study, with 802 versus 792 Gt for 2010 as shown in (Krausmann et al., 2017b).These in-use stocks remain in service for years to decades, therefore in 2014 end-of-life wastes from stocks were at 16 Gt/yr much lower than gross additions to stock (Fig. 3D). The model further calculated that in summary across all 14 materials categories 39% of end-of-life wastes from stocks were re- and down-cycled in 2014.

The results shown agree well with an extensive validation against the available literature on in-use stocks of specific materials or substances (Cao et al., 2017; Gerst and Graedel, 2008; Geyer et al., 2017; Glöser et al., 2013; Krausmann et al., 2017b; Lauk et al., 2012; Liu and Müller, 2013; Müller et al., 2013; Pauliuk et al., 2013; Rauch, 2009; Rauch and Graedel, 2007; Rauch and Pacyna, 2009). The detailed comparisons can be found in the Supplementary Information 1.

4. Using Monte-Carlo Simulations and Global Sensitivity Analysis to Quantify and Attribute Uncertainty

In our modelling framework we utilize Monte-Carlo Simulations (MCS) to quantify uncertainty in model outputs due to variability in model input parameters. We then apply several local sensitivity tests and apply a Global Sensitivity Analysis to attribute sources of uncertainty in model results to the respective model input parameters.

Based on an extensive literature review, uncertainty ranges for all model inputs were derived and propagated to model outputs (see SI). The required number of MCS to achieve relatively stable model output results has been simulated at > 2000 simulations (see SI), herein we used 10,000 simulations.

A number of methods for global and local sensitivity analysis are available to better understand the behaviour of the model itself, to consider variability in model outputs due to specific input parameters, and ultimately to attribute all model output variations to different sources of model input uncertainty (Borgonovo and Plischke, 2016; Norton, 2015; Pianosi et al., 2016).

Herein, we investigate local model sensitivity, firstly by quantifying the isolated effects of changes to the lifetime distributions on in-use stocks. We find that even substantial changes to lifetime distributions, e.g. +50% longer lifetimes, only increase stock estimates by 9% for the year 2014 (see SI for a summary of 7 different sensitivity tests, Fig. S10). Secondly, we check the sensitivity of stock estimates for each material against all relevant exogenous model input parameters, to check for non-uniform and unexpected model behaviour (Pianosi et al., 2016). We conclude that there seem to be no locally specific nor unexpected sensitivities of the model outputs to certain parameter spaces (see SI, Fig. S10).

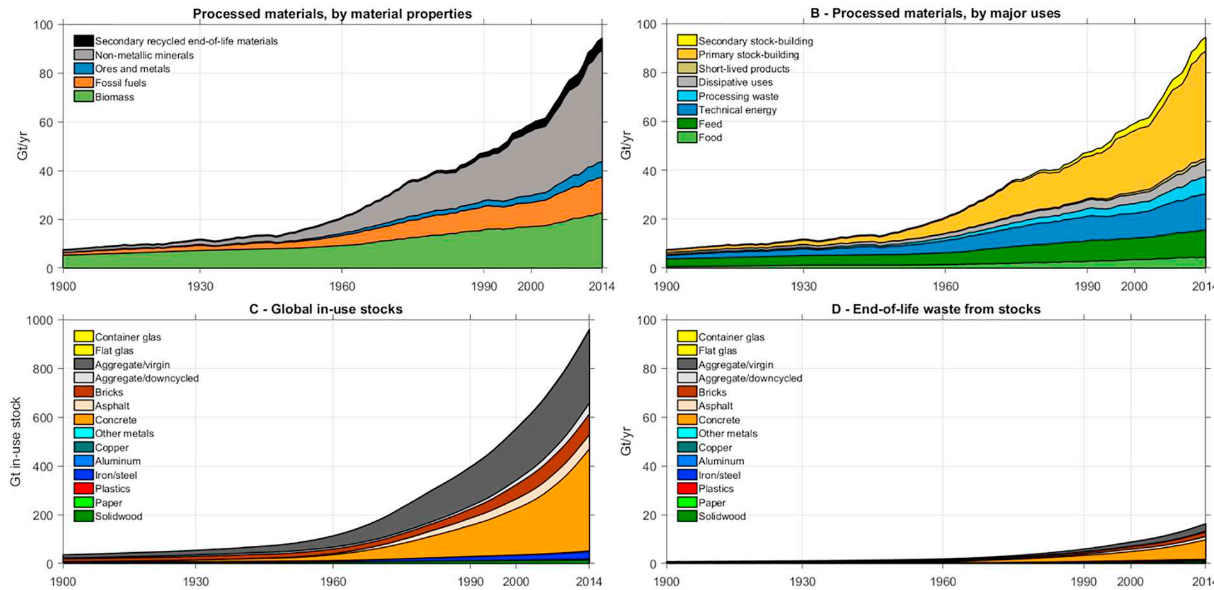

Fig. 3. Global material stocks and flows, from 1900 to 2014. Annual flows of primary and secondary processed materials (A), processed materials by use (B), in-use stocks (C) and end-of-life waste from stocks (D). Note that A, B and D share the same y-axis scaling, while the y-axis of C is one magnitude larger. Data from Fig. 3 can be found in the SI.

Herein, in terms of Global Sensitivity Analysis, we utilize Spearman's rank correlation coefficient to attribute first-order effects on the uncertainty of in-use stocks and end-of-life waste from stocks to the relevant exogenous model input parameters. This procedure underestimates higher order interaction effects between model parameters (Borgonovo and Plischke, 2016; Saltelli and Sobol, 1995). However, due to an insufficient empirical basis to properly quantify uncertainties and probability density functions for all exogenous model inputs, we would argue that more complex methods for Global Sensitivity Analysis (Džubur et al., 2016; Norton, 2015; Pianosi et al., 2016), are not yet appropriate (see Section 9 on next steps).

We find that for total uncertainty of global total in-use stock estimates, the most important materials are aggregates and bricks, and in the second half of the 20th century also concrete and asphalt (Fig. 4A). In terms of model input parameters, uncertainties about lifetime distributions and primary material inflows are the major factors for overall in-use stock uncertainty, while secondary material inputs and recycling rates, which are partially dependent on each other, seem to be minor factors (Fig. 4B) – however the potential for higher-order effects between these partially dependent parameters should be checked with more complex Global Sensitivity Analysis methods. We also find that for the uncertainty of end-of-life waste from stocks, variability in lifetime distributions are the dominant source of variation, while uncertainty of total in-use stocks are only responsible for about 10% of total uncertainty (Fig. 4C), which is line with previous research (Miatto et al., 2017a).

Similar tests for each of the 14 different materials under investigation show some differences in the main sources of uncertainty, which are also changing over time depending on the accumulated level of in-use stock of each material and the mean lifetime of each material (see SI, Figs. S8–9). Uncertainties in lifetime distributions and in primary as well as secondary material inputs to stocks are usually the most important model input parameters for the resulting uncertainty of in-use stocks (see SI, Fig. S8). For end-of-life waste from stocks, uncertainty in in-use stock estimates and variability introduced by the lifetime

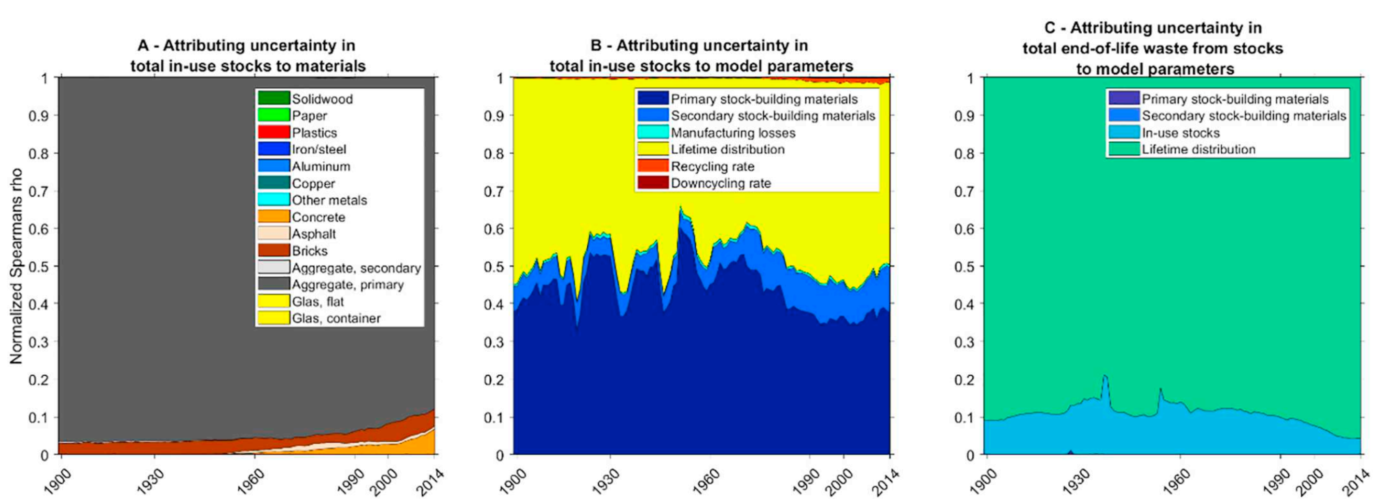

Fig. 4. Attribution of total uncertainty for total global in-use stock, by material (A) and exogenous model input parameter (B), as well as for total uncertainty of end-of-life waste from stocks, by model input parameter (C). All figures share the same y-axis, 100% of total uncertainty. The uncertainty attribution is calculated as the sum of all spearman's rank correlation coefficients rho for each material and model parameter. Statistical significance has been set at $p = 0.05$ and results are normalized (SI for details).

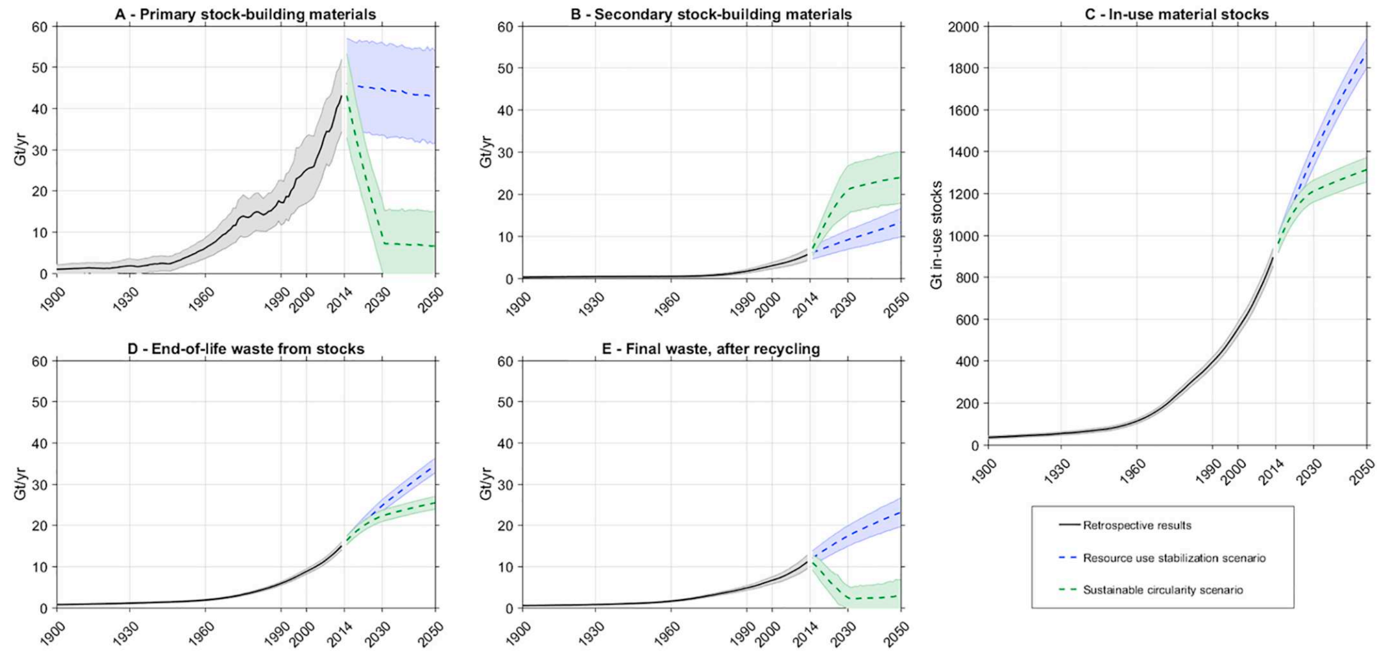

Fig. 5. Results from two prospective scenarios of the global dynamics of primary[2] (A) and secondary (B) material inputs into stocks, global in-use stocks of manufactured capital (C), end-of-life waste from stocks (D) and final waste after recycling (E). Note that figures A, B, D & E share the same y-axis scaling, while C does not. Uncertainty ranges are expressed as ± three standard deviations over 10^5 Monte-Carlo Simulations. Data from Fig. 5 can be found in the SI.

distributions are clearly the most important factors determining uncertainty of end-of-life waste estimates provided by the model, also when checking the individual materials (see SI, fig. S9).

5. Using the MISO-Model to Explore Possible Futures of the Socioeconomic Metabolism until 2050: Two Exemplary Scenarios

The MISO-model is also designed to explore future option spaces for the socioeconomic metabolism by providing stock-flow consistent and biophysically feasible scenarios. Clearly, any desirable sustainable futures will require more services provided by in-use stocks of manufactured capital (e.g. adequate housing, clean energy, …), while absolutely reducing environmental pressures and impacts (Akenji et al., 2016; Haberl et al., 2017). These multiple goals require careful assessment and delineation, which go beyond the scope of this paper and will require substantially expanded modelling capabilities. Herein, we present two exemplary scenarios to showcase the MISO-scenario approach and show the importance of taking stock dynamics into account.

Firstly, we model a *resource use stabilization* of primary resource use at the global scale. This is a key part of ongoing discussions about contraction and convergence where industrial countries would reduce their resource use to enable catching-up of developing countries while keeping global environmental pressures stable (UNEP, 2011). Along this line, in this scenario we assume that global primary stock-building material consumption is stabilized and all other parameters of the model remain at their levels in 2014, which would already constitute a major effort in the face of continuous and unabated growth of global resource use (Schandl et al., 2017).

In this *Resource use stabilization* scenario, end-of-life wastes from stocks more than double until 2050, from 15.7 Gt/yr in 2014 to 34.5 Gt/yr in 2050 (Fig. 5D). These materials are partially recycled into secondary stock-building materials (Fig. 5B). The increase in secondary materials in combination with the constant inflow of primary stock-building materials[2] (Fig. 5A) results in a slight increase of annual stock-building from 49.8 Gt/yr in 2014, to 54.1 Gt/yr in 2050. Subsequently, global in-use stocks are projected to double from 928 Gt in 2014, to 1869 Gt in 2050. However, final waste remaining after recycling also doubles to 23.2 Gt/yr in 2050 (Fig. 4E). Despite this assumed stabilization of primary resource use, pressures on the environment are therefore expected to further increase, because of the modelled doubling of waste flows, which require treatment and management for recycling and deposition. On the positive side, the projected doubling of in-use stocks indicates substantially expanded capabilities to provide services to society.

Secondly, we explore the role of stocks in a simplified *sustainable circularity scenario*, where we assume that globally re-use and recycling are strongly implemented, enabling an absolute reduction of primary resource use. This scenario would go a long way towards ecological sustainability due to massively reduced environmental pressures associated with resource extraction and waste production. For this purpose, we assume that re- and downcycling rates increase to 90% between 2015 and 2030 and primary material use decreases by −90%. Both parameters are then held constant until 2050.

In this *sustainable circularity* scenario, final waste flows after recycling are substantially reduced to only 2.8 Gt/yr in 2050, or 24% of the modelled amounts in 2014 (Fig. 5E). Due to aging in-use stocks and drastically improved recycling, increasingly more secondary materials become available for stock maintenance and even expansion (24 Gt/yr in 2050), in spite of the assumed absolute reduction of primary material inflows to only 6.6 Gt/yr (Fig. 5A,B,D). Subsequently, global in-use stocks still increase by 42% compared to 2014, to 1314 Gt in 2050 (Fig. 5C). Interestingly, these modelled levels of in-use stocks are only 1/3 lower than in the *resource use stabilization* scenario. This shows that in this simplified *sustainable circularity* scenario, substantial progress towards sustainability can be achieved if the circular economy is

[2] Please note that the demand for primary aggregates is calculated from the gap between secondary aggregates available and the requirements for sand and gravel due to the quantities of asphalts, bricks and concrete, as well as sub-base and base-course layers (see SI for details). Therefore, the *global stabilization* scenario shows slight reductions of primary stock-building materials (Figure 5A), caused by the increased availability of secondary aggregates due to increasing end-of-life wastes from stocks and their recycling.

(*footnote continued*)

implemented with the goal to absolutely reduce resource use. At the same time, a further expansion of in-use stocks required to provide more services to a growing global population is easily possible.

These two examples show, how the MISO-model provides stock-flow consistent scenarios on potentially more sustainable resource use patterns and why taking stock dynamics explicitly into account is so important to understand potential futures. A number of additional scenario parameters are available in the MISO-model: while obviously all exogenous model input parameters can be used as scenario drivers and the endogenous model outputs are then the scenario results, as in the two examples above, these endogenous results could also be used as 'targets' to explore the respective biophysical stock-flow requirements, however these efforts are beyond the scope of this paper.

6. Limitations and Next Steps

As shown, the MISO-model currently yields results on in-use stocks of materials and the resulting end-of-life waste and recycling flows at the global scale. Next steps include investigations of world-regions and countries, using available ew-MFA databases and country-level industrial production statistics, as well as the development of more sophisticated scenarios.

In regards to the handling of uncertainty, in the MISO-model Monte-Carlo Simulations are successfully used to propagate uncertainty about exogenous model input variables throughout all endogenous modelling results. Issues of uncertainty have been further assessed by investigating local and global model sensitivities and by attributing the uncertainty of model results to input data and model parameters, in order to inform next steps in data gathering and model improvements (see section 7 and SI). Importantly, currently the uncertainty ranges for exogenous model parameters are derived by combining available literature and expert judgements (see SI and (Krausmann et al., 2017b) for details). This means that current results on uncertainty and sensitivity are only a first step in method development and understanding model behaviour. An improved empirical basis for uncertainty quantifications needs to be developed, as part of a larger effort in systematically handling uncertainty in MFA and dynamic MFA modelling (Džubur et al., 2016; Krausmann et al., 2017a; Laner et al., 2014). Both, empirically derived uncertainty estimations and further differentiation of physical flows and stocks by stock-types and spatial scale will be part of these improvements. Applying more complex Global Sensitivity Assessment methods to quantify, analyse and assess uncertainty and sensitivity would then become justified and insightful (Borgonovo and Plischke, 2016; Džubur et al., 2016; Laner et al., 2014; Pianosi et al., 2016).

A more substantial next step is the introduction of a more functional perspective on in-use stocks, for example by discerning machinery, mobility infrastructure from residential and commercial buildings. Practically, this requires information on the specific uses of stock-building materials, e.g. clarifying which quantities are used to build which kinds of stocks. A comprehensive implementation for all stock-building materials covered herein can build on previous work for specific materials and stock-types (Cao et al., 2017; Cullen et al., 2012; Cullen and Allwood, 2013; Liu and Müller, 2013; Miatto et al., 2017b; Pauliuk et al., 2013). Such a stock-type differentiation would enable using not only normal lifetime distributions, but also log-normal, Weibull, or Gompertz distributions, depending on the specific stock-type and subject to available information for parametrization (Miatto et al., 2017a).

While it has been shown that different functional forms used as lifetime distributions do not substantially affect the results for in-use stocks, modelled dynamics of end-of-life waste can differ substantially (Miatto et al., 2017a). Because official waste statistics are often incomplete and of poor quality (Moriguchi and Hashimoto, 2016; Tisserant et al., 2017), the comprehensive and mass-balanced systems approach presented herein would then provide more robust estimates for waste and recycling flows.

Such a mass-balanced economy-wide assessment of all socio-economic stocks and flows could then be used to inform efforts in monitoring and assessing the global to national biophysical circular economy (Haas et al., 2015), which is currently being implemented by the European Union as part of the Circular Economy policy package (European Commission, 2018b; Jacobi et al., 2018; Mayer et al., in print). The MISO-modelling could then provide consistent estimates of the non-linear dynamics of end-of-life waste and recycling potentials due to aging stocks, additional to incomplete information from waste statistics and to provide estimates of future waste and circularity potentials as well as scenarios.

7. Conclusions

Economy-wide material flow accounting and derived indicators have so far focused on quantifying resource extraction, physical trade, apparent consumption and so-called material footprints. Herein, we present a systematic extension of the established ew-MFA framework, utilizing a dynamic inflow-driven modelling of Material Inputs, Stocks and Outputs (MISO-model v1). This model enables a fully mass-balanced tracing of materials from extraction, trade and consumption, throughout stock-building, accumulation as in-use stocks of manufactured capital, as well as subsequent non-linear temporal dynamics of end-of-life waste and recycling potentials. Monte-Carlo Simulations and Global Sensitivity Analysis are used to quantify, evaluate, and attribute uncertainty to model data and parameters. The model is designed in a flexible manner and can be applied at any scale, given sufficient long-term material flow data availability – which usually are available on the national to global level.

In this paper, we applied the MISO-model to the global socio-economic metabolism to estimate in-use stock, recycling and waste dynamics from 1900 to 2014, extending previous work beyond 2010 (Krausmann et al., 2017b). We find that since the year 2010, primary resource use and secondary materials increased by 3.5% on average per year, further eroding global sustainability. The share of secondary recycled materials in total inflows is at around 6%, indicating a continuously low level of loop closing since a previous global assessment for 2005 (Haas et al., 2015). At the same time, global in-use stocks of manufactured capital grew at ~3.9% per annum since 2010, providing more and more services to society, but also driving future resource and energy use and waste potentials.

We further showcased how the MISO-model can be used for prospective scenarios by taking the crucial role of in-use stocks of manufactured capital for the dynamics of the socio-economic metabolism seriously. Interestingly, in an exploratory prospective *sustainable circularity* scenario, a radical dematerialization of −90% reduction of primary stock-building materials, coupled with substantial improvements in global recycling systems, still results in 42% in-use stock expansion until 2050. This means that even absolute reductions of resource use, which would be tremendous progress in terms of reducing environmental pressures, still can go hand in hand with increases in global in-use stocks of manufactured capital and therefore improved infrastructure, continuing urbanization and an expansion of services provided by stocks (e.g. mobility, shelter, …).

In conclusion, the MISO-extended ew-MFA approach can now make substantial next steps towards fulfilling the systematic, mass-balanced and dynamic systems perspective included in the theoretical basis of this method (see Section 2 and (Fischer-Kowalski and Weisz, 1999; Pauliuk and Hertwich, 2015; Pauliuk and Müller, 2014). These new capabilities then constitute a starting point for innovative contributions to exploring the Stock-Flow-Service Nexus (Haberl et al., 2017) and identifying biophysical option spaces towards a more sustainable socioeconomic metabolism.

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Author Contributions

D.W., F·K., T.F. and W.H. designed the research; D.W., T.F. and C.L. developed the model as well as the sensitivity and uncertainty assessments; D.W. implemented the model and all sensitivity and uncertainty procedures; F.K, D.W., W.H. and C.L. prepared data and performed calculations. D.W. and T.F. wrote the paper, while all others contributed to writing the paper.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.09.010.

References

Adriaanse, A., World Resources Institute (Eds.), 1997. Resource Flows: The Material Basis of Industrial Economies. World Resources Institute, Washington, D.C..

Akenji, L., Bengtsson, M., Bleischwitz, R., Tukker, A., Schandl, H., 2016. Ossified materialism: introduction to the special volume on absolute reductions in materials throughput and emissions. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2016.03.071.

Altimiras-Martin, A., 2014. Analysing the structure of the economy using physical input–output tables. Econ. Syst. Res. 26, 463–485. https://doi.org/10.1080/09535314.2014.950637.

Augiseau, V., Barles, S., 2016. Studying construction materials flows and stock: a review. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2016.09.002.

Ayres, R.U., Simonis, U.E. (Eds.), 1994. Industrial Metabolism: Restructuring for Sustainable Development. United Nations University Press, Tokyo; New York.

Bahn-Walkowiak, B., Steger, S., 2015. Resource targets in Europe and worldwide: an overview. Resources 4, 597–620. https://doi.org/10.3390/resources4030597.

Borgonovo, E., Plischke, E., 2016. Sensitivity analysis: a review of recent advances. Eur. J. Oper. Res. 248, 869–887. https://doi.org/10.1016/j.ejor.2015.06.032.

Bornhöft, N.A., Sun, T.Y., Hilty, L.M., Nowack, B., 2016. A dynamic probabilistic material flow modeling method. Environ. Model Softw. 76, 69–80. https://doi.org/10.1016/j.envsoft.2015.11.012.

Bringezu, S., 2015. Possible target corridor for sustainable use of global material resources. Resources 4, 25–54. https://doi.org/10.3390/resources4010025.

Bringezu, S., Potočnik, J., Schandl, H., Lu, Y., Ramaswami, A., Swilling, M., Suh, S., 2016. Multi-scale governance of sustainable natural resource use—challenges and opportunities for monitoring and institutional development at the national and global level. Sustainability 8, 778. https://doi.org/10.3390/su8080778.

Bruel, A., Kronenberg, J., Troussier, N., Guillaume, B., 2018. Linking industrial ecology and ecological economics: a theoretical and Empirical Foundation for the circular economy: linking IE and EE: a Theoretical Foundation for CE. J. Ind. Ecol. https://doi.org/10.1111/jiec.12745.

Brunner, P.H., Rechberger, H., 2017. Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers, Second Edition. CRC Press, Taylor & Francis Group, Boca Raton.

Cabrera Serrenho, A., Allwood, J.M., 2016. Material stock demographics: cars in Great Britain. Environ. Sci. Technol. 50, 3002–3009. https://doi.org/10.1021/acs.est.5b05012.

Cao, Z., Shen, L., Løvik, A.N., Müller, D.B., Liu, G., 2017. Elaborating the history of our cementing societies: an in-use stock perspective. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.7b03077.

Chen, W.-Q., Graedel, T.E., 2012. Anthropogenic cycles of the elements: a critical review. Environ. Sci. Technol. 46, 8574–8586. https://doi.org/10.1021/es3010333.

Cullen, J.M., Allwood, J.M., 2013. Mapping the global flow of aluminum: from liquid aluminum to end-use goods. Environ. Sci. Technol. 47, 3057–3064. https://doi.org/10.1021/es304256s.

Cullen, J.M., Allwood, J.M., Bambach, M.D., 2012. Mapping the global flow of steel: from steelmaking to end-use goods. Environ. Sci. Technol. 46, 13048–13055. https://doi.org/10.1021/es302433p.

Dafermos, Y., Nikolaidi, M., Galanis, G., 2017. A stock-flow-fund ecological macroeconomic model. Ecol. Econ. 131, 191–207. https://doi.org/10.1016/j.ecolecon.2016.08.013.

Daigo, I., Igarashi, Y., Matsuno, Y., Adachi, Y., 2007. Accounting for steel stock in Japan. ISIJ Int. 47, 1065–1069.

Daigo, I., Iwata, K., Ohkata, I., Goto, Y., 2015. Macroscopic evidence for the hibernating behavior of materials stock. Environ. Sci. Technol. 49, 8691–8696. https://doi.org/10.1021/acs.est.5b01164.

Dombi, M., Karcagi-Kováts, A., Tóth-Szita, K., Kuti, I., 2018. The structure of socio-economic metabolism and its drivers on household level in Hungary. J. Clean. Prod. 172, 758–767. https://doi.org/10.1016/j.jclepro.2017.10.220.

Džubur, N., Buchner, H., Laner, D., 2016. Evaluating the use of global sensitivity analysis in dynamic MFA: global sensitivity analysis in dynamic MFA. J. Ind. Ecol. https://doi.org/10.1111/jiec.12497.

Economic, U.N., Social Council, 2016. Progress towards the Sustainable Development Goals (Report of the Secretary - General). United Nations.

Eisenmenger, N., Wiedenhofer, D., Schaffartzik, A., Giljum, S., Bruckner, M., Schandl, H., Wiedmann, T.O., Lenzen, M., Tukker, A., Koning, A., 2016. Consumption-based material flow indicators — comparing six ways of calculating the Austrian raw material consumption providing six results. Ecol. Econ. 128, 177–186. https://doi.org/10.1016/j.ecolecon.2016.03.010.

European Commission, 2011. Roadmap to a Resource Efficient Europe (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions). Brussels.

European Commission, 2018a. On a Monitoring Framework for the Circular Economy (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM (2018) 29 Final {SWD(2018) 17 Final}). Brussels.

European Commission, 2018b. Measuring Progress Towards Circular Economy in the European Union – Key Indicators for a Monitoring Framework (Comission Staff Working Document No. SWD(2018) 17 final, COM(2018) 29 final), Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a Monitoring Framework for the Circular Economy. Strasbourg.

Eurostat, 2001. A methodological guide. In: Economy-Wide Material Flow Accounts and Derived Indicators. Eurostat, European Commission, Office for Official Publications of the European Communities, Luxembourg.

Fischer-Kowalski, M., Weisz, H., 1999. Society as a hybrid between material and symbolic realms. Toward a theoretical framework of society-nature interaction. Adv. Hum. Ecol. 8, 215–251.

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting: state of the art and reliability across sources. J. Ind. Ecol. 15, 855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x.

Fishman, T., Schandl, H., Tanikawa, H., Walker, P., Krausmann, F., 2014. Accounting for the material stock of nations: accounting for the material stock of nations. J. Ind. Ecol. 18, 407–420. https://doi.org/10.1111/jiec.12114.

Fishman, T., Schandl, H., Tanikawa, H., 2016. Stochastic analysis and forecasts of the patterns of speed, acceleration, and levels of material stock accumulation in society. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.5b05790.

García-Torres, S., Kahhat, R., Santa-Cruz, S., 2017. Methodology to characterize and quantify debris generation in residential buildings after seismic events. Resour. Conserv. Recycl. 151–159. https://doi.org/10.1016/j.resconrec.2016.11.006.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The circular economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Gerst, M.D., Graedel, T.E., 2008. In-use stocks of metals: status and implications. Environ. Sci. Technol. 42, 7038–7045. https://doi.org/10.1021/es800420p.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782. https://doi.org/10.1126/sciadv.1700782.

Giljum, S., Hubacek, K., 2004. Alternative approaches of physical input–output analysis to estimate primary material inputs of production and consumption activities. Econ. Syst. Res. 16, 301–310. https://doi.org/10.1080/0953531042000239383.

Giljum, S., Dittrich, M., Lieber, M., Lutter, S., 2014. Global patterns of material flows and their socio-economic and environmental implications: a MFA study on all countries world-wide from 1980 to 2009. Resources 3, 319–339. https://doi.org/10.3390/resources3010319.

Glöser, S., Soulier, M., Tercero Espinoza, L.A., 2013. Dynamic analysis of global copper flows. Global stocks, postconsumer material flows, recycling indicators, and uncertainty evaluation. Environ. Sci. Technol. 47, 6564–6572. https://doi.org/10.1021/es400069b.

Glöser-Chahoud, S., Tercero Espinoza, L., Walz, R., Faulstich, M., 2016. Taking the step towards a more dynamic view on raw material criticality: an indicator based analysis for germany and Japan. Resources 5 (4), 45.

Haas, W., Krausmann, F., Wiedenhofer, D., Heinz, M., 2015. How circular is the global economy?: an assessment of material flows, waste production, and recycling in the European Union and the world in 2005. J. Ind. Ecol. 19, 765–777. https://doi.org/10.1111/jiec.12244.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., Winiwarter, V., 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21, 199–213.

Haberl, H., Wiedenhofer, Dominik, Erb, Karl-Heinz, Görg, Christoph, Krausmann, Fridolin, 2017. The material stock–flow–service Nexus: a new approach for tackling the decoupling conundrum. Sustainability 9, 1049. https://doi.org/10.3390/su9071049.

Hashimoto, S., Tanikawa, H., Moriguchi, Y., 2009. Framework for estimating potential wastes and secondary resources accumulated within an economy – a case study of construction minerals in Japan. Waste Manag. 29, 2859–2866. https://doi.org/10.1016/j.wasman.2009.06.011.

Heeren, N., Hellweg, S., 2018. Tracking construction material over space and time: prospective and geo-referenced modeling of building stocks and construction material flows: tracking construction material. J. Ind. Ecol. https://doi.org/10.1111/jiec.12739.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies.

Proc. Natl. Acad. Sci. 112, 6277–6282. https://doi.org/10.1073/pnas.1312753111.
Jacobi, N., Haas, W., Wiedenhofer, D., Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges. Resour. Conserv. Recycl. 137, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022.
Kovanda, J., 2017. Total residual output flows of the economy: methodology and application in the case of the Czech Republic. Resour. Conserv. Recycl. 116, 61–69. https://doi.org/10.1016/j.resconrec.2016.09.018.
Kovanda, J., Havranek, M., Hak, T., 2007. Calculation of the "net additions to stock" indicator for the Czech Republic using a direct method. J. Ind. Ecol. 11, 140–154. https://doi.org/10.1162/jiec.2007.1155.
Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.H., Haberl, H., Fischer-Kowalski, M., 2009. Growth in global materials use, GDP and population during the 20th century. Ecol. Econ. 68, 2696–2705.
Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S., Jackson, T., 2017a. Material flow accounting: global material use and sustainable development. Annu. Rev. Environ. Resour. 42. https://doi.org/10.1146/annurev-environ-102016-060726.
Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H., Haberl, H., 2017b. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. 114 (8), 1880–1885.
Krausmann, F., Lauk, C., Haas, W., Wiedenhofer, D., 2018. From resource extraction to outflows of wastes and emissions: the socioeconomic metabolism of the global economy, 1900–2015. Glob. Environ. Chang. 52, 131–140. https://doi.org/10.1016/j.gloenvcha.2018.07.003.
Krook, J., Baas, L., 2013. Getting serious about mining the technosphere: a review of recent landfill mining and urban mining research. J. Clean. Prod. 55, 1–9. https://doi.org/10.1016/j.jclepro.2013.04.043.
Laner, D., Rechberger, H., Astrup, T., 2014. Systematic evaluation of uncertainty in material flow analysis. J. Ind. Ecol. 18, 859–870. https://doi.org/10.1111/jiec.12143.
Lauk, C., Haberl, H., Erb, K.-H., Gingrich, S., Krausmann, F., 2012. Global socioeconomic carbon stocks in long-lived products 1900–2008. Environ. Res. Lett. 7, 034023.
Lin, C., Liu, G., Muller, D.B., 2017. Characterizing the role of built environment stocks in human development and emission growth. Resour. Conserv. Recycl. 123, 67–72. https://doi.org/10.1016/j.resconrec.2016.07.004.
Liu, G., Müller, D.B., 2013. Centennial evolution of aluminum in-use stocks on our aluminized planet. Environ. Sci. Technol. 47, 4882–4888. https://doi.org/10.1021/es305108p.
Lwin, C.M., Dente, S.M.R., Wang, T., Shimizu, T., Hashimoto, S., 2017. Material stock disparity and factors affecting stocked material use efficiency of sewer pipelines in Japan. Resour. Conserv. Recycl. 123, 135–142. https://doi.org/10.1016/j.resconrec.2016.08.010.
Majeau-Bettez, G., Pauliuk, S., Wood, R., Bouman, E.A., Strømman, A.H., 2016. Balance issues in input–output analysis: a comment on physical inhomogeneity, aggregation bias, and coproduction. Ecol. Econ. 126, 188–197. https://doi.org/10.1016/j.ecolecon.2016.02.017.
Malik, A., McBain, D., Wiedmann, T.O., Lenzen, M., Murray, J., 2018. Advancements in input-output models and indicators for consumption-based accounting: MRIO models for consumption-based accounting. J. Ind. Ecol. https://doi.org/10.1111/jiec.12771.
Martinico-Perez, M.F.G., Schandl, H., Fishman, T., Tanikawa, H., 2018. The socio-economic metabolism of an emerging economy: monitoring progress of decoupling of economic growth and environmental pressures in the Philippines. Ecol. Econ. 147, 155–166. https://doi.org/10.1016/j.ecolecon.2018.01.012.
Mathews, J.A., Tan, H., 2016. Circular economy: lessons from China. Nature 531, 440–442. https://doi.org/10.1038/531440a.
Matthews, E., Amann, C., Bringezu, S., Fischer-Kowalski, M., Hüttler, W., Kleijn, R., Moriguchi, Y., Ottke, C., Rodenburg, E., Rogich, D., Schandl, H., Schütz, H., van der Voet, E., Weisz, H., 2000. The Weight of Nations: Material Outflows from Industrial Economies. World Resources Institute, Washington, DC.
Mayer, A., Haas, W., Wiedenhofer, D., 2017. How countries' resource use history matters for human well-being – an investigation of global patterns in cumulative material flows from 1950 to 2010. Ecol. Econ. 134, 1–10. https://doi.org/10.1016/j.ecolecon.2016.11.017.
Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A., 2018. Measuring progress towards a circular economy - a monitoring framework for economy-wide material loop closing in the EU28. J. Ind. Ecol. https://doi.org/10.1111/jiec.12809. (in print).
Meadows, D.H., Meadows, D.H., Randers, J., Behrens III, W.W., 1972. The Limits to Growth: A Report to the Club of Rome. Universe Books, New York.
Miatto, A., Schandl, H., Tanikawa, H., 2017a. How important are realistic building lifespan assumptions for material stock and demolition waste accounts? Resour. Conserv. Recycl. 122, 143–154. https://doi.org/10.1016/j.resconrec.2017.01.015.
Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F., Tanikawa, H., 2017b. Modeling material flows and stocks of the road network in the United States 1905–2015. Resour. Conserv. Recycl. 127, 168–178. https://doi.org/10.1016/j.resconrec.2017.08.024.
Ministry of the Environment Japan, 2016. Annual Report on the Environment in Japan 2016. Government of Japan, Tokyo.
Moriguchi, Y., Hashimoto, S., 2016. Material Flow Analysis and Waste Management. In: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer International Publishing, Cham, pp. 247–262. https://doi.org/10.1007/978-3-319-20571-7_12.
Müller, D.B., 2006. Stock dynamics for forecasting material flows—case study for housing in The Netherlands. Ecol. Econ. 59, 142–156.
Müller, D.B., Wang, T., Duval, B., 2011. Patterns of iron use in societal evolution. Environ. Sci. Technol. 45, 182–188. https://doi.org/10.1021/es102273t.
Müller, D.B., Liu, G., Løvik, A.N., Modaresi, R., Pauliuk, S., Steinhoff, F.S., Brattebø, H., 2013. Carbon emissions of infrastructure development. Environ. Sci. Technol. 47, 11739–11746. https://doi.org/10.1021/es402618m.
Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014a. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. 48, 2102–2113. https://doi.org/10.1021/es403506a.
Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014b. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. 48, 2102–2113. https://doi.org/10.1021/es403506a.
Nakamura, S., Kondo, Y., 2009. Waste Input-Output Analysis: Concepts and Application to Industrial Ecology, Eco-Efficiency in Industry and Science. Springer, Dordrecht.
Nguyen, R.T., Imholte, D.D., 2016. China's rare earth supply chain: illegal production, and response to new cerium demand. JOM 68, 1948–1956. https://doi.org/10.1007/s11837-016-1894-1.
Norton, J., 2015. An introduction to sensitivity assessment of simulation models. Environ. Model Softw. 69, 166–174. https://doi.org/10.1016/j.envsoft.2015.03.020.
OECD, 2008. Measuring material flows and resource productivity. In: The OECD Guide. Vol. 1 OECD, Paris.
OECD, 2015. Material resources, productivity and the environment. In: OECD Green Growth Studies. OECD Publishing. https://doi.org/10.1787/9789264190504-en.
O'Neill, D.W., 2015. What should be held steady in a steady-state economy?: interpreting Daly's definition at the National Level: what should be held steady in a steady-state economy? J. Ind. Ecol. 19, 552–563. https://doi.org/10.1111/jiec.12224.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1, 88–95. https://doi.org/10.1038/s41893-018-0021-4.
Ortlepp, R., Gruhler, K., Schiller, G., 2015. Material stocks in Germany's non-domestic buildings: a new quantification method. Build. Res. Inf. https://doi.org/10.1080/09613218.2016.1112096.
Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019.
Pauliuk, S., Hertwich, E.G., 2015. Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies. Ecol. Econ. 119, 83–93. https://doi.org/10.1016/j.ecolecon.2015.08.012.
Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Chang. 24, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006.
Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30. https://doi.org/10.1016/j.resconrec.2012.11.008.
Pauliuk, S., Wood, R., Hertwich, E.G., 2015. Dynamic models of fixed capital stocks and their application in industrial ecology: a dynamic model of the industrial metabolism. J. Ind. Ecol. 19, 104–116. https://doi.org/10.1111/jiec.12149.
Pauliuk, S., Arvesen, A., Stadler, K., Hertwich, E.G., 2017. Industrial ecology in integrated assessment models. Nat. Clim. Chang. 7, 13–20. https://doi.org/10.1038/nclimate3148.
Pianosi, F., Beven, K., Freer, J., Hall, J.W., Rougier, J., Stephenson, D.B., Wagener, T., 2016. Sensitivity analysis of environmental models: a systematic review with practical workflow. Environ. Model Softw. 79, 214–232. https://doi.org/10.1016/j.envsoft.2016.02.008.
Rauch, J.N., 2009. Global mapping of Al, Cu, Fe, and Zn in-use stocks and in-ground resources. Proc. Natl. Acad. Sci. 106, 18920–18925. https://doi.org/10.1073/pnas.0900658106.
Rauch, J.N., Graedel, T.E., 2007. Earth's anthrobiogeochemical copper cycle: copper cycle. Glob. Biogeochem. Cycles 21https://doi.org/10.1029/2006GB002850. (n/a-n/a).
Rauch, J.N., Pacyna, J.M., 2009. Earth's global Ag, Al, Cr, Cu, Fe, Ni, Pb, and Zn cycles: global metal cycles. Glob. Biogeochem. Cycles 23https://doi.org/10.1029/2008GB003376. (n/a-n/a).
Reyna, J.L., Chester, M.V., 2014. The growth of urban building stock. J. Ind. Ecol. 19, 524–537. https://doi.org/10.1111/jiec.12211.
Saltelli, A., Sobol, I.M., 1995. About the use of rank transformation in sensitivity analysis of model output. Reliab. Eng. Syst. Saf. 50, 225–239. https://doi.org/10.1016/0951-8320(95)00099-2.
Sandberg, N.H., Brattebø, H., 2012. Analysis of energy and carbon flows in the future Norwegian dwelling stock. Build. Res. Inf. 40, 123–139. https://doi.org/10.1080/09613218.2012.655071.
Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014. The global metabolic transition: regional patterns and trends of global material flows, 1950–2010. Glob. Environ. Chang. 26, 87–97. https://doi.org/10.1016/j.gloenvcha.2014.03.013.
Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Krausmann, F., Gierlinger, S., Hosking, K., Lenzen, M., Tanikawa, H., Miatto, A., Fishman, T., 2017. Global material flows and resource productivity: forty years of evidence: global material flows and resource productivity. J. Ind. Ecol. https://doi.org/10.1111/jiec.12626.
Schiller, G., Müller, F., Ortlepp, R., 2016. Mapping the anthropogenic stock in Germany: metabolic evidence for a circular economy. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2016.08.007.
Schiller, G., Müller, F., Ortlepp, R., 2017. Mapping the anthropogenic stock in Germany: metabolic evidence for a circular economy. Resour. Conserv. Recycl. 123, 93–107. https://doi.org/10.1016/j.resconrec.2016.08.007.
Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China:

moving from rhetoric to implementation. J. Clean. Prod. 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020.
Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2015. Aluminium for the future: modelling the global production, market supply, demand, price and long term development of the global reserves. Resour. Conserv. Recycl. 103, 139–154. https://doi.org/10.1016/j.resconrec.2015.06.008.
Takiguchi, H., Takemoto, K., 2008. Japanese 3R policies based on material flow analysis. J. Ind. Ecol. 12, 792–798. https://doi.org/10.1111/j.1530-9290.2008.00093.x.
Tanikawa, H., Fishman, T., Okuoka, K., Sugimoto, K., 2015. The weight of society over time and space: a comprehensive account of the construction material stock of Japan, 1945-2010. J. Ind. Ecol. 19, 778–791. https://doi.org/10.1111/jiec.12284.
Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., Tukker, A., 2017. Solid waste and the circular economy: a global analysis of waste treatment and waste footprints: global analysis of solid waste and waste footprint. J. Ind. Ecol. 21, 628–640. https://doi.org/10.1111/jiec.12562.
Turner, G.M., Hoffman, R., McInnis, B.C., Poldy, F., Foran, B., 2011. A tool for strategic biophysical assessment of a national economy – the Australian stocks and flows framework. Environ. Model Softw. 26, 1134–1149. https://doi.org/10.1016/j.envsoft.2011.03.007.
UNEP, 2011. Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. United Nations Environment Programme, Nairobi.
UNEP, 2016. Global Material Flows and Resource Productivity. Assessment Report for the UNEP International Resource Panel. United Nations Environment Programme, Paris.
Weisz, H., Suh, S., Graedel, T.E., 2015. Industrial ecology: the role of manufactured capital in sustainability. Proc. Natl. Acad. Sci. 112, 6260–6264. https://doi.org/10.1073/pnas.1506532112.
Wiedenhofer, D., Steinberger, J.K., Eisenmenger, N., Haas, W., 2015. Maintenance and expansion: modeling material stocks and flows for residential buildings and transportation networks in the EU25. J. Ind. Ecol. 19, 538–551. https://doi.org/10.1111/jiec.12216.
Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112, 6271–6276. https://doi.org/10.1073/pnas.1220362110.
Yang, W., Kohler, N., 2008. Simulation of the evolution of the Chinese building and infrastructure stock. Build. Res. Inf. 36, 1–19.