RESEARCH AND ANALYSIS

Quo vadis MFA?
Integrated material flow analysis to support material efficiency

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Abstract
Material efficiency (ME) strategies are pursued by governments and companies to reduce environmental emissions, improve supply chain resilience, and enhance cost competitiveness. Material flow analysis (MFA) methods are useful to quantify raw material stocks and flows and assess the potential impacts of ME strategies. Although the popularity of MFA methods is increasing, there are methodological limitations that hinder its use as a decision support tool for prospective assessments. To overcome some of these, MFA is increasingly integrated with other methods from different research fields. This paper categorizes integrated MFA methods by identifying and explaining the methods and their applications. A semi-structured literature review screened a wide range of methods integrated with MFA prospective analysis and evaluated their applications from 158 studies. This showed that integrated MFA can be used to: (1) include economic, social, and environmental layers; (2) improve the technical foundation of MFA by including entropy and exergy analyses and process engineering methods; (3) include economic mechanisms and link the economic system to the material system; and (4) improve the representation of materials in existing methods and models. Our research demonstrates that integrated MFA should be a central method in planning and designing ME strategies for companies and governments. This paper provides an important knowledge base of integrated MFA methods and creates a discussion point on MFA, where the research field is currently at or indeed where it could be heading in the future, that is, “Quo Vadis” MFA.

KEYWORDS
business strategy, decision support, industrial ecology, material efficiency, material flow analysis (MFA), policy analysis

1 INTRODUCTION

Raw material extraction and use are a large and increasing source of global greenhouse gas (GHG) emissions. GHG emissions for the production of materials grew by 120% from 1995 to 2015 and accounted for 23% of global GHG emissions in 2015 (Hertwich, 2021). With the growth in material consumption over the last decades and the expected continuation of this trend, reducing material-related emissions is becoming
increasingly important (IEA, 2019; IRP, 2020). In addition, the materials of 21st century technologies are becoming more complex (Greenfield & Graedel, 2013), and important low carbon technologies such as transport electrification result in increased material demands and new challenges (Bleicher & Pehlken, 2020). While traditionally often overlooked in the climate mitigation debate (IEA, 2020), material efficiency (ME) strategies are seen as great opportunities to reduce GHG emissions (Hertwich et al., 2019; Rissman et al., 2020), enhance cost competitiveness (Bleischwitz, 2010; Flachenecker et al., 2017), and improve supply chain resilience (Gaudstad et al., 2018; Tercero Espinoza et al., 2020). Such strategies largely include material demand reduction, product lifetime extension, dematerialization, material substitution, reducing material losses in production and supply chains, and material recovery through reuse or recycling (Hertwich et al., 2019; Olivetti & Cullen, 2018; Worrell et al., 2016).

To assess the potential impacts of ME strategies and inform decision makers, prospective quantitative assessments using industrial ecology methods are needed (Masanet et al., 2021; Pauliuk & Hertwich, 2016). One widely applied method for that purpose and the focus of this paper is material flow analysis (MFA) (Graedel, 2019; Singh et al., 2021; Walzberg et al., 2021). MFA can be applied across different geographical (e.g., process, firm, sectors, regions, countries) and material scales (e.g., substance, components, goods, and aggregated material categories) (Brinzeu et al., 2009; OECD, 2008; Wiedmann et al., 2006). What is considered MFA, however, is not always clear and different methods have been labeled under the term MFA. Here, we define MFA as a method family and adopt a part of the topology used by Villalba et al. (2018). Hence, we include the following methods under the MFA umbrella: Static and dynamic substance flow analysis (SFA), static and dynamic individual material flow analysis (iMFA), and economy-wide material flow accounting (ew-MFA) (see Supporting Information 1, Chapter S1 for more detail). MFAs can be utilized in two ways. First, it can describe past or current flows and stocks of materials in a spatial and temporal defined system, that is, descriptive accounting type assessments such as ew-MFA. Second, MFA can be used to examine the impacts of future changes on material systems, that is, change-oriented prospective assessments, which are here referred to as prospective MFA (Brunner & Rechberger, 2016; de Haes et al., 2000; Finnveden & Moberg, 2005). Prospective MFA is therefore useful to assess the potential impacts of ME strategies, which is the focus of this research.

MFA is increasingly used in academia and its potential as decision support tool is recognized. The method however has several limitations that could hinder its use in company and governmental decision-making. These include, that is, the lack of a general framework for MFA methods (Binder, 2007); incompleteness and fragmentation of data (Müller et al., 2018); difficulty to interpret the results due the descriptive nature of stock and flows measurements (Baccini & Brunner, 2012; Brunner, 2002); absence of economic mechanisms in MFA models (Manderson & Considine, 2018; Pfaff et al., 2018; Winning et al., 2017); and the typically low technological detail that can miss important physical constraints (Gaustad et al., 2011; van Schalk & Reuter, 2010).

To overcome some of these limitations and improve MFA as a decision support tool, it is widely argued that MFA should be integrated with methods from different research fields. Some scholars have conceptualized this as MFA extensions (Huang et al., 2012), integrated MFA (Graedel, 2019), MFA interfaces (Bode et al., 2012), or comprehensive MFA-based assessments (Brunner, 2002) (see also Table S1). These integrations are here referred to as integrated material flow analysis (integrated MFA). We propose four reasons for integrated MFA. First, MFA can be linked with additional information layers that have different units of measurements, such as environmental (e.g., CO₂ emissions) or cost (e.g., US$), to improve the evaluation and interpretation of MFA results (Baccini & Brunner, 2012; Brunner, 2002; Brunner & Rechberger, 2016; Huang et al., 2012; Islam & Huda, 2019). Second, MFA can be integrated with process engineering methods to enhance the technical foundation of MFA (Bode et al., 2012; Denz et al., 2014; Fröhling et al., 2012). Third, MFA can be integrated with economic models to include economic mechanisms (allocation, optimization, substitution) into physical systems (Binder, 2007; Bouman et al., 2000; Pfaff et al., 2018). Fourth, MFA can be integrated with operations research and complex systems science to include dynamics, feedbacks, and optimizing behavior based on simulation and optimization methods (Lambrecht & Thißen, 2015; Moeller et al., 2010; Walzberg et al., 2021).

Despite the calls for integrated MFA, an overview and assessment of methods that can be integrated with MFA is currently missing. Previous MFA literature reviews focus on specific materials or sectors such as metal cycles (Chen & Graedel, 2012; Müller et al., 2014), construction materials (Augiseau & Barles, 2017), electronic waste (Islam & Huda, 2019), the built environment (Lanau et al., 2019), or methodological aspects such as dynamic MFA models (Müller et al., 2014) without clearly reviewing or categorizing integrated MFA. Some authors have identified and discussed the use of integrated MFA for specific applications, such as material criticality (Olivetti et al., 2015), social science models (Binder, 2007) and integrating MFA with sustainability assessment (Huang et al., 2012). Building on these discussions, this paper aims to review and categorize methods integrated with MFA to assess the potential impacts of ME strategies. Accordingly, the objectives of this research are:

1. to identify methods integrated with MFA from different research fields and their application;
2. to categorize the different methods and purposes for integration with MFA by giving some examples;
3. to show the scopes, purposes, and methods of integrated MFA in different decision-making contexts

A semi-structured literature review to screen a wide range of integrated MFA methods was conducted and their application evaluated. This paper therefore provides an important knowledge base of integrated MFA and creates a starting point for discussions on MFA and where the research field is or indeed should be going in the future, that is, “Quo Vadis MFA.”
2 | METHODOLOGY

Due to the lack of standardization, the different terminologies used, and the interdisciplinary nature of MFA, conducting a systematic review is insufficient to identify most integrated MFA methods and corresponding literature. Instead, a semi-systematic literature review that screens the different applications of integrated MFA is needed. Semi-systematic review, also referred to as meta-narrative review, is a relatively new review method designed for topics that have been conceptualized and studied by different research groups (Snyder, 2019; Wong et al., 2013). The method helps to develop an account of a multidisciplinary topic, such as MFA, and shows how this topic has evolved over time. It provides a rich, although not necessarily complete, picture of relevant studies that are linked to MFA. The literature selection was an iterative process, which followed a four-step procedure as illustrated in Figure 1.

In the first step, integrated MFA methods were identified through an iterative process and a database search in Scopus was conducted to identify corresponding studies (see the search terms used in Supporting Information S1, Chapter S2). The identified methods should cover at least one of the four aims for integrated MFA as described in the introduction, that is, add additional information layers to evaluate MFA results, enhance the technical detail, include economic mechanisms, and include dynamics, feedbacks, and optimizing behavior. A total of 802 studies were identified and further analyzed to obtain the most relevant studies for the second step. Here two main criteria were used to further filter the most important studies. First, the study must link one of the established MFA methods to a different method (see Figure 2). Our definition of established MFA method includes static and dynamic SFA, static and dynamic individual MFA, and ew-MFA, similar to the MFA typology by Villalba et al. (2018) but excludes multiregional and input–output analysis (IOA). IOA is excluded from our definition of established MFA methods for the following reasons. IOA is not consistent with the system structure of MFA. IOA includes markets and its system is represented as a bipartite directed graph, whereas in MFA, markets are generally not included and its system is represented as a directed graph. Furthermore, the generality of the mathematical model of MFA (flows can enter any mathematical relationship as long as mass balance is preserved) does not fit the more restricted model of IOA based on specific accounting rules (Pauliuk et al., 2015). Based on this, we focus on studies that integrate MFA with methods outside the MFA community. Studies that link different types of MFAs are therefore not included (e.g., ew-MFA and dynamic MFA [Wiedenhofer et al., 2019], or substance flow analysis and individual MFA [Stanisavljevic & Brunner, 2014]). The second criterion to filter the literature selection is that studies must adopt a prospective outlook that investigates scenarios of future flows and stocks, including static scenario and dynamic models. Hence, studies must be change-oriented and simple accounting studies are excluded. Based on this, a total of 98 studies were selected. In step 3, the full article was read and classified based on several characteristics, including bibliographic, methodological, and decision-making characteristics. Finally, in step 4, an additional 58 studies were found through backward and forward snowballing of references, a common technique used in meta-narrative reviews (Greenhalgh et al., 2005). A further elaboration of the methodology steps can be found in Chapters S1 and S2 of Supporting Information S1.
3 RESULTS AND DISCUSSION

3.1 Identifying integrated MFA methods

A wide variety of methods ranging from process engineering to economics were identified that have been linked to MFA methods across spatial scales. All methods included in this review are listed in Figure 2 and grouped by their method family, including evaluation, structural simulation based, and optimization methods. Based on the identified linked methods to MFA, a total of 158 studies were found and included in the review (see the Excel file [Supporting Information S2] for the complete overview of studies and characteristics). Over 80% were published after 2012 (Figure S1 of Supporting Information S1). The studies were published in a wide variety of journals (158 studies in 54 journals), although half of the studies were published in just 5 journals. Furthermore, based on the intercitation (amount of times studies in the database cite each other), 44% of the studies are not linked (see Figures S2 and S3 of Supporting Information S1). The following sections briefly discuss each method and their applications to MFA.

3.1.1 MFA and evaluation-based methods

Evaluation-based methods are integrated into MFA to include additional layers of information (e.g., monetary value, environmental emissions) to evaluate material systems and thereby establish a multilayer MFA approach (Hamilton et al., 2015; Villalba et al., 2018). They can be divided into sustainability impact evaluations, including economic, environmental, and social impact evaluation methods and material quality evaluations methods, including entropy and exergy.

Evaluating environmental impact in MFA is primarily based on life cycle assessment (LCA). A total of 33 studies link LCA and MFA for prospective assessments, the largest number of studies compared to other integration methods. Combining MFA with LCA was first proposed by Tukker et al. (1997) and implemented with a case study by Laner and Rechberger (2007) on the impact of different material-recovery strategies for cooling appliances. Most studies link LCA to MFA to evaluate both the environmental and material impacts of possible changes in material systems, thus adding an environmental layer to physical material flows. The LCA method, and, in particular, resource-related life cycle impact assessment (LCIA) categories can also benefit from the use of MFA results. Examples include the proposed method by Charpentier Poncelet et al. (2019), who coupled (dynamic) MFA with LCI and LCIA categories to improve the nonenergetic abiotic resource use in LCA or the approach by Wiesen and Wirges (2017) who established the material footprint indicator for LCA by adapting the ecoinvent database based on MFA principles.

Economic evaluations of MFA found in the literature (11 studies were identified) were based on material flow cost accounting (MFCA), life cycle costing (LCC), discounted cash flow (DCF), and cost benefit analysis (CBA). The distinction between these four methods and their application to MFA can primarily be made on the level of the analysis. On a company and supply chain level, MFCA is used to evaluate and identify possible cost savings from ME in companies and supply chains (Schmidt et al., 2015; Schmidt & Nakajima, 2013). However, MFCA is essentially a retrospective accounting method and only seven MFCA studies were identified that model prospective material flows, and some combined it with environmental data (obtained through LCA). This corresponds with the observations by Schaltegger and Zvezdov (2015), who conclude that the prospective use of MFCA information has been mostly neglected. On a project-based level, CBA and the closely related DCF are used to evaluate the economic feasibility of different ME strategies, in particular, waste-recovery strategies. DCF, a widely used method in decision-making about the economic future of primary mineral deposit (Kesler & Simon, 2015) was first used by Winterstetter et al. (2015) to illustrate that a combination of MFA with
DCF analysis is useful in classifying anthropogenic deposits into economically extractable reserves and resources based on the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources (UNFC) (UNECE, 2010). Lastly, LCC is linked to MFA by assessing the costs related to ME strategies on products, such as recycling of waste mobile phones (He et al., 2020) and photovoltaic technologies (Marwede & Reller, 2014).

Social evaluation of MFA can be based on social life cycle assessment (SLCA), of which only one study was found (Pillain et al., 2019) that assessed the future direct and indirect employment opportunities from a new recycling sector (carbon fibers from the aeronautical industry). Sixteen studies combined one or two impact assessment methods with MFA, of which (14) combine cost accounting methods with LCA to analyze the environmental and economic performance of ME strategies on product, company, supply chain, and national level.

To evaluate the physical performance, or the quality of material systems, two methods that are linked to MFA are statistical entropy analysis (SEA) and exergy analysis (EA). SEA is used to study the quality changes of material flow systems and thus the performance of material systems (i.e., the concentration vs. distribution of substances in material flows) (Rechberger & Graedel, 2002). Five studies that use SEA in combination with MFA for prospective assessments were identified. Based on SEA, all studies use the relative statistical entropy (RSE) metric (a dimensionless value in the range 0–1, $H$, defined by the ratio $H/H_{\text{max}}$; see also Rechberger and Brunner (2002) for the mathematical background of SEA) to determine the dilution of substances and compare scenarios of different ME strategies. Due to the direct applicability of SEA on MFA databases and little requirement for additional computing (Brunner & Rechberger, 2016), SEA has been applied on both a micro (e.g., waste battery sieving process [Velázquez Martínez et al., 2019]) and macro scale (e.g., European copper system [Rechberger & Graedel, 2002]). Exergy analysis is combined with MFA as an indicator to determine the quality of the material system, that is, the higher level of exergy, the more the flow deviates from the equilibrium state of the environment (Brunner & Rechberger, 2016). Most integrated MFA–EA studies are accounting studies measuring the material and exergy flow of retrospective systems. Only two studies were identified that integrate MFA and EA in a prospective manner to model future impacts of different strategies for planning purposes, both on a facility (Yang & Liu, 2016) and national level (Michaelis & Jackson, 2000). An additional approach to evaluate the quality of material systems is the inclusion of elemental composition of chemical compounds and goods in MFA. Such approach has also been linked with optimization models (discussed later) to formulate waste cascading optimization problems and include elemental level contamination as constraint (e.g., maximum concentration of metallic elements to produce aluminum [Løvik et al., 2014; Van Schaik et al., 2002] or steel [Ohno et al., 2017] alloys from end-of-life vehicles).

3.1.2 MFA and simulation-based methods

Simulation-based MFA models (found in 23 studies) study the dynamic behavior of material and energy stocks and flows over time. They can be further differentiated into discrete event simulation (DES), agent-based simulation (ABS), system dynamics (SD), and process simulation (PS) models. On the most detailed level, PS refers to steady-state and dynamic simulation models based on physical laws (mass balance) used in chemical and process engineering to analyze, design, and improve production processes. Five studies were identified that linked MFA with PS. The main motivation of this linkage is to solve the lack of granularity for the modeling of processes and data availability. For industrial use, for example, existing chemical engineering PS tools can be linked with material flow (cost) models to identify and improve resource efficiency at plant level (Bode et al., 2012; Viere et al., 2014).

Five studies link MFA to DES models to simulate material flows on a factory level and identify bottlenecks and improve the process chains from an environmental or economic point of view. MFA–SD (eight studies identified) are applied on the regional and supply chain level with the purpose to simulate (nonlinear) behavioral mechanisms behind physical material flows, such as modeling of dynamic behavior of ME measures in the German copper cycle (Pfaff et al., 2018), substituting steel with aluminum in car bodies with aluminum in Australia (Stasinopoulos et al., 2011), or global indium flows related to LED lamps, solar PV, and indium tin oxide (ITO) production (Choi et al., 2016). The scope and applications of MFA–ABS (four studies identified) are similar to MFA–SD studies, but depend on how behavior is modeled (SD is driven by a global system behavior based on differential equations while ABS models are decentralized models that simulate the behavior of individual agents; see also Bollinger et al. (2012) for a comparison between the two for modeling of material flow systems).

3.1.3 MFA and optimization-based methods

Optimization-based models refer to the class of models that is used to find optimal system configurations when alternatives are present based on one or several defined objective and system constraints. Optimization-based MFA are further classified into elastic (EDO) and non-elastic demand optimization (NEDO) models based on the way in which supply and demand interact. NEDO-MFA are used to find the optimal system configurations based on technology choices, objective functions, and (physical) constraints assuming a fixed exogenous given demand. A total of 25 studies applied combined NEDO-MFA in different contexts, for example, company, supply chain, and regional levels. NEDO is combined with MFA to (1) allow
for endogenous technology choices where multiple alternative options are present (e.g., Gaustad et al. (2011)), (2) illustrate trade-offs between objectives if combined with other LCIA categories or economic costs (e.g., Lambrecht et al. (2017)), and (3) increase the calculation efficiency of complex problems (e.g., Cooper et al. (2020)). EDO models on the other hand do not assume fixed demand and instead consider that supply and demand interact based on price adjustments. EDO can be further differentiated into partial equilibrium (PE) models that include only one or few sectors of the economy or computational general equilibrium (CGE) models that include all sectors and therefore focus on the whole economy. Combined use of MFA and EDO was found in 30 studies, (12 PE and 18 CGE). From an MFA point of view, this combination is used to capture market responses related to changes in the physical material system, such as technical ME strategies (Skelton et al., 2020) or changes in trade policies (Lenglet et al., 2017; Pothen, 2013). The integration of MFA into established EDO and NEDO models, such as integrated assessment and energy optimization models, has been pursued to include materials into the models, which are typically ignored (Kullmann et al., 2021; Pauliuk et al., 2017). Obrist et al. (2021), for example, include materials into the TIMES energy model to assess the climate mitigation potentials in the Swiss cement industry and Seck et al. (2020) integrate materials into a global TIMES model to assess the future copper demand in relation to energy system scenarios.

### 3.1.4 MFA and structural methods

The fourth kind of method used in combination with MFA is the structural models (10 studies were identified to use this type of integration). Structural models may be further differentiated into input–output (IO) analysis and macro-econometric (MEC) models. MFA has been linked to monetary IO tables (MIOT) to establish scenarios of future material flows across all sectors of the economy, such as the MaTrace model by Nakamura et al. (2014) to estimate the future fate of materials of all products manufactured in the past based on a static, retrospective MIOT or its dynamic extension including future product demand and waste based on a dynamic stock model and product lifetimes (Nakamura & Kondo, 2018). MEC can be regarded as a dynamic extension of IO that includes supply–demand interactions in the model and are similar to CGE. Two studies were identified that integrate ew-MFA into existing MEC models, the E3M3 model (Cambridge Econometrics, 2019) and GINFORS (Global Interindustry Forecasting System) (Meyer & Lutz, 2007) to study the economy wide and material impacts of related policies.

Based on the mentioned facts, Table 1 provides a summary of the purpose and scope of integrated MFA methods. A detailed discussion of each integrated MFA method is provided in Chapter S5 of Supporting Information S1.

### 4 INTEGRATED MFA IN DIFFERENT DECISION-MAKING CONTEXTS

The choice of methodologies that can be integrated with MFA should be guided by the decision-making context and the practical problems that need to be solved. The following section provides an overview of integrated MFA in various decision-making contexts. The decision-making context is divided into micro and meso/macro level decisions based on the typology used in the International Reference Life Cycle Data System (ILCD) handbook (JRC, 2010) and the classification of MFA methods by Daniels and Moore (2001). Micro level refers to ME decisions on a process, company, and product supply chains, which is primarily targeting engineers and business managers at the company level. Meso and macro refer to more public policy-oriented ME decisions on a regional, national, or global level, respectively (see Figure 3).
| Category                | Method                          | Purpose of integration                                                                 | Example                                                                 |
|-------------------------|---------------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Evaluation              | Life cycle assessment           | Environmental emissions related to material flows; improve resource-related life cycle impact assessment | Future projections of the environmental impacts and reduction potential of Japanese wood consumption (Kayo et al., 2018) |
|                         | Life cycle costing              | Economic feasibility of material efficiency-related strategies on a product level       | Assessing the life cycle cost of historic and future waste mobile and smart phone recycling in China (He et al., 2020) |
|                         | Cost benefit analysis/discounted case flow | Economic feasibility of material efficiency-related strategies on product and regional level | Identify profitability of recycling rare earth elements from lighting technologies (Qiu & Suh, 2019) |
|                         | Material flow cost accounting   | Evaluate and identify material cost savings in companies and supply chains              | Economic and environmental benefits of material efficiency improvements in a latex manufacturing company in Sri Lanka (Dunuwila et al., 2020) |
| Social life cycle assessment | Social life cycle assessment   | Social impact related to the material system                                            | Future job potential in the French carbon fiber aeronautical recycling sector (Pillai et al., 2019) |
| Statistical entropy analysis | Statistical entropy analysis | Evaluate the dilution or concentration of substance and materials based on relative statistical entropy | Statistical entropy of different efficiency strategies in the Austrian phosphorus cycle (Laner et al., 2017) |
| Exergy analysis         | Exergy analysis                 | Evaluate the availability of energy stored in material flows (exergy)                   | Future exergy consumption in the UK steel sector under different technical scenarios (Michaelis & Jackson, 2000) |
| Simulation              | Discrete event                  | Discrete simulation of material flows in the material systems                           | Simulate the impacts of reducing the semiconductor wafer size in a production company (Wohlgemuth et al., 2006) |
|                         | Agent based                     | Simulation of material flows driven by the interaction of supply chain actors based on clearly defined rules | Future global market trajectories in the neodymium and dysprosium supply chain (Riddle et al., 2015) |
|                         | System dynamics                 | Simulation of material flows driven by a global system behavior-based on differential equations | Future changes and feedbacks in the Chinese lithium supply chain (Sun et al., 2019) |
|                         | Process simulation              | Simulation of individual process in a more detailed manner based on thermo-dynamic valid relations | Identify plant level resource improvements in the chemical industry in Germany (Viere et al., 2014) |
| Optimization            | Non-elastic demand optimization | Identify optimal system configurations based on one or several objective functions when several production alternatives are possible, demand is exogenous and fixed | Dynamic criticality of future global copper supply based on future demand projections and mine locations (Seck et al., 2020) |
|                         | Partial equilibrium             | Simulate material markets based on endogenous demand and supply interaction, limited to one or few economic sectors | Impact of material policies on future sand extraction (Hoogmartens et al., 2018) |
|                         | General equilibrium             | Similar to partial equilibrium but includes all economic sectors                       | Impact of different building stock development and floor space demand on economy-wide CO₂ in China (Cao et al., 2019) |
| Structural              | Input-output analysis           | Physical flows of one or several economic sectors based on conversion of monetary IO tables using scenarios or dynamic IO to forecast material flows | Analyzing the functional losses of steel alloy in Japan over several product cycles due to function losses and contamination (Nakamura et al., 2017) |
|                         | Macro-econometric              | Based on econometric relation of IO tables used to model future material flows and the impacts of policies | Impact of material and carbon productivity of environmental tax reform in the European Union including material tax (Ekins et al., 2012) |
4.1 | Process level

On the process level, integrated MFA models can have three main purposes. First, the integration of exergy and entropy-based methods into MFA helps to evaluate the physical quality of the material system based on the second law of thermodynamics. In this regard, statistical entropy analysis (SEA) is useful to evaluate how materials are diluted throughout the material system due to its ease of linking to MFA, that is, no additional data collection is required, and can be implemented across scales (micro and macro) (Laner et al., 2021) and materials (substances and goods) (Parchomenko et al., 2021).

Second, integrating MFA with process and chemical engineering-based assessments can improve the technical detail at the process level. This provides MFA with more technical details and makes the method more useful for engineering-based design and process planning (Fröhling et al., 2012). Steady-state and dynamic PS methods can be used, and PS software helps to model processes and elemental flows in more detail, providing more reliable data for life cycle inventories (LCIs) and MFA. These applications have been recognized since the 1990s (Ayres, 1995; Radgen et al., 1998; Reuter, 1998), but are not widely implemented within current MFA studies. A linkage between MFA and PS software such as ASPEN, CHEMCAD, or HC SIM (e.g., integration of the MFA–LCA software; see Umberto and CHEMCAD [Viere et al., 2014]) could therefore make the physical base of MFA more robust (e.g., including the physical limitations of recycling [Reuter, 2011]). Such an approach could also be used to optimize the design of products from a recycling point of view by accounting for physical limitations based on metallurgical knowledge, for example, linkage of LED light (Reuter & van Schaik, 2015) or solar photovoltaic panel designs (Bartie et al., 2021) to PS software.

From a complementary point of view, linking MFA to PS models could benefit the latter by providing the link between several PS submodels of larger systems (e.g., facility level) without the need for a simulation of the whole facility level (Viere et al., 2014). To enable integrated MFA on the process level, a further linkage between MFA research and chemical and process engineering should be established including method and software developments. A particular subfield of interest is process system engineering (PSE) where the importance of multiscale modeling (from molecular to supply chain design and second to years), the circular economy, and data-driven methods are recognized (Pistikopoulos et al., 2021). Current EA studies, for example, are typically based on simulated or average data. This limits its use to inform industrial plant operators on ME improvements (Michalakis & Cullen, 2021). Instead, low-cost sensors and big data methods, which are also important PSE tools (Edgar & Pistikopoulos, 2018; Pistikopoulos et al., 2021), can be used to support decision-making (Michalakis & Cullen, 2021).

4.1.1 | Company level

The company level context refers to material systems related to the process chain in a single facility. Integrated MFA on a company level can have two main purposes. First, by including environmental and economic aspects, company managers and engineers can assess the potential material cost and emission savings of improved efficiency within facilities or inform decisions on the sustainability of material procurement strategies. MFCA and LCA provide the most useful and well-established methods in this regard. Several examples can be found throughout the literature. Kluczek (2019) for instance combines MFA, LCA, and MFCA to evaluate the eco-efficiency (economic cost vs. environmental impact) of various process-improvement scenarios in a boiler production company. Similarly, Dunuwila et al. (2020) utilize the same methods to assess the financial and environmental sustainability of material flow improvements for concentrated latex factories in Sri Lanka. Only a few software solutions are currently available for MFCA (Kunisch & Wohlgemuth, 2019) and further software developments should be established. The MFA software STAN, for example, could be used to include company level money flows as illustrated by Müller (2013) or integrate material, cost, and emissions layers into one package as done in the Umberto software (Schmidt et al., 2013).

The second purpose for integrated MFA on a company level is to simulate and identify optimal strategies and trade-offs of ME improvements (Moeller et al., 2010). To simulate the dynamics of material flows in process chains and model the impacts of potential changes, integrated MFA and DES models can be established and further coupled with LCA or cost methods for evaluation purposes. Alvandi et al. (2015), for instance, used this approach for an aluminum recycling and rolled sheet production facility to identify and simulate energy-saving opportunities on a factory level combining MFA–LCA software (Umberto) with a simulation software (Anylogic). Process-based NEDO models can be further used to identify optimal choices when several alternatives are available and illustrate contrasting objectives (i.e., economic, environmental, and material improvements), such as illustrated in the case of process decisions for a German tungsten producer (Lambrecht et al., 2017). Further software developments and linkage to operations research methods should be established. An example here is the prototype software solution by Lambrecht et al. (2017), combining an MFCA and LCA software (Umberto) with an optimization software (LINDO) to identify optimal (economic and environmental) solutions in company production systems.

4.1.2 | Supply chain level

The supply chain level refers to material systems related to a single product across several life cycle stages (extraction, production, use, and disposal) and spatial scales (neighborhood to global level). Supply chain level studies fall typically in between micro and meso level decision contexts but
are here categorized as micro-level that study a single product system. Integrated MFA on this level has three purposes. First, the establishment of multilayers material flow models based on materials, cost, and emissions can help evaluate the impacts of material-efficient product and supply chain design options. In this regard, integrated LCA-MFA models are increasingly established to include environmental layers into MFA and evaluate the emission reduction potential of technical strategies. Due to the time-specificity of MFA, LCA, for instance, are integrated with dynamic MFA models to embodied emissions of materials and assess the environmental benefits of ME strategies over time such as the bio-based material (straw) for thermal retrofitting (Göswein et al., 2020) or compare different technical material efficient strategies for the residential housing stock (Heeren & Hellweg, 2019; Lausselet et al., 2020). A procedural framework combining MFA and LCA was developed by Wiprächtiger et al. (2020) to evaluate ME strategies in product systems in a more structured manner. Aggregated MFA data is here linked to LCA based on the modular MFA–LCA approach proposed by Haupt et al. (2018), and a dynamic MFA is used to evaluate the environmental performance of ME strategies for products. A further inclusion of an economic layer by linking MFA–LCA with environmental LCC can be established but has received not as much attention. In this regard, MFCA could also be useful to add additional economic layers to material flow supply chain assessment (Christ & Burritt, 2015; ISO, 2017), such as the coupled MFCA-LCA model to assess cost reduction, carbon mitigation, and revenue generation of ME strategies for black current juice production in Germany (May & Guenther, 2020), or to integrate LCA and LCC as proposed by Bierer et al. (2015). For more complex systems with several alternatives or contrasting objectives (i.e., environmental, material, and economic), optimization models can be used to identify optimal product strategies within the decision space. Examples of this approach are illustrated by Mehr et al. (2018) on optimal wood use strategies for residential housing and Gao and You (2018) to identify optimal shale gas supply chain designs. Furthermore, product level material criticality assessments in combination with prospective MFA and supply chain network analysis as imagined by Nuss et al. (2016) could be established. Such assessments provide a comprehensive picture of current and future material supply chain risks and can be useful product design decisions.

The second purpose for integrated MFA on the supply chain level is to improve resource-related LCA impact categories. One possibility here is to use dynamic MFA to include the flows of substances in the technosphere, their quality and dissipation and product lifetime (Charpentier Poncelet et al., 2019; Schaubroeck et al., 2020). A case study to address the dissipation of abiotic resources in LCA is presented by Charpentier Poncelet et al. (2021).

The third purpose for integrated MFA on a supply chain level is to include economic mechanisms to understand how product supply chains might be affected due to changes in the material system. Integrated MFA and agent based simulation (ABS) and SD models can be used to simulate potential feedbacks in product supply chains such as substituting steel car bodies with aluminum (Stasinopoulos et al., 2011) or reuse strategies for phones (Bollinger et al., 2012). MFA and PE models can also be used to include market processes and simulate economic behavior. Here the economic material–product chain model developed by Kandelaars and van den Bergh (1997) and extended by Schwarz (2006) provides a mathematical framework that links material and product flows to an economic model to evaluate the effects of policy measures. One key limitation of these models at such aggregated product level is the difficulty to obtain demand elasticity parameters (the percentage of change in demand for products or materials following a change in price). A fixed demand optimization model (NEDO) could be used instead, providing less modeling sophistication than PE (demand is fixed rather than endogenously determined) but a higher level of technical detail as recognized in related LCA models (Katelhon et al., 2016).

Overall, software developments could further enable the integration of MFA with LCA and LCC. The modular open-source LCA software developed by Steubing et al. (2016), for example, is useful to establish MFA–LCA models and can be linked to optimization models as illustrated by Mehr et al. (2018). The Open Dynamic Material Systems Model (ODYM) (Pauliuk & Heeren, 2019) can also be used in combination with LCA to track materials and consider time and material quality for circular economy product systems (Schaubroeck et al., 2020). A further integration of MFA into the life cycle sustainability analysis (LCSA) framework could also be established to position and operationalize MFA in combination with LCA, LCC, and SLCA (see also Hu et al. (2013) for operational steps for this approach). Finally, a further integration of MFA in the field of operations research and supply chain management could be a potential endeavor benefiting both fields of research (Blass & Corbett, 2018).

### 4.1.3 Regional level

The regional level refers to material systems on a sectorial level within regions defined by administrative border ranging from municipality to sub-national government. The purpose of integrated MFA on this level is two folded. First, MFA is integrated with evaluation methods to assess the economic or environmental benefits of ME strategies on a regional level. Such integrations are important to evaluate the sustainability of strategies to enable a regional circular economy (Meglin et al., 2021; OECD, 2020). For example, environmental layers are added to study the impact of strategies in municipal or electronic waste management systems on an urban and regional level using integrated MFA–LCA models (De Meester et al., 2019; Thushari et al., 2020; Turner et al., 2016). Similarly, economic layers based on CBA or other cost methods are used to study the economic performance such as material improvements in urban waste management (de Kraker et al., 2019; Villarroel Walker et al., 2017) or both environmental and economic performance through MFA–LCA–CBA integration (Rochat et al., 2013). MFCA in combination with LCA could also be applied on the regional level, as illustrated by Shibata and Matsumoto (2008) on the assessment of different recycling scenarios for organic house-
hold waste in a Japanese region. Furthermore, multiobjective optimization (NEDO) can be used to identify optimal material strategies minimizing cost and emissions while maximizing material recovery, such as regional sewage sludge (Vadenbo, Guillén-Gosálbez, et al., 2014; Vadenbo, Hellweg, et al., 2014) or municipal organic waste improvements (Cobo et al., 2019).

The second purpose of integrated MFA models on the regional level is to include economic mechanisms. The most promising methods for this purpose are SD, ABM PE, and NEDO. MFA–SD and MFA–ABM models can be used to include cause–effect relationships and behaviors of agents, which can be used to facilitate regional policy-making related to a single sector (e.g., agro-food networks or materials used by the construction industry) (Fernandez-Mena et al., 2020; Kytzia et al., 2020) or economy-wide material systems (Gao et al., 2020). A regionalized version of the material–product chain framework could also be used to include economic mechanisms in MFA. Lessard et al. (2021), for instance, use the material–product chain framework to identify regional winners and losers in the Canadian and US cement sector due to an increase in secondary material in cement production by reducing the clinker-to-cement ration by 2050. Models that include all economic sectors (CGE, IO, or ME) and capture potential rebound effects on a regional level are less common due to the difficulty of obtaining relevant regional data (Beaussier et al., 2019).

### 4.1.4 National and global level

The meso/macro context refers to the material systems on a national or global level with a sectoral (i.e., related to one or several sectors) or economy-wide level (i.e., the whole economy) aimed to support strategic policy decisions. The main reasons to integrate MFA with other methods in this context are similar to the regional level. First, MFA is integrated with evaluation methods to establish multilayer MFA able to assess the economic, environmental, or physical impacts of ME strategies on national (or global) level. Through integrated MFA–LCA models, environmental evaluations of efficiency improvements related to one or several sectors on the macro level can be explored. Dong et al. (2020) and Kayo et al. (2018), for instance, model future pathways for copper and wood demand in China and Japan, respectively and evaluate the environmental impacts of different scenarios. In a similar way, Pauliuk et al. (2020) establish the resource efficiency–climate change (RECC) mitigation framework, linking material production and recycling GHG intensity parameters to a multilayer dynamic MFA of major product groups. The inclusion of economic aspects could further enhance the understanding of efficiency strategies and the decision relevance of MFA for national (or global) policy makers. Relevant work in this regard is the linkage of MFA with cost–benefit analysis to evaluate the economic feasibility of recycling. For example, low metal contents in products and poor market conditions make recycling not always economically feasible (e.g., recycling rare earth elements from waste lighting technologies [Qiu & Suh, 2019] or extracting metals from landfills [Winterstetter et al., 2016]). Understanding the economic viability of mining anthropogenic resource stocks could help policy makers to understand if potential interventions in secondary markets are required when market failures occur and setting the right incentives to enhance recycling (Söderholm & Ekvall, 2019). An important continuous research direction in this regard is the use of MFA as mining prospecting tool for anthropogenic resources, such as the linkage of MFA and DCF and the classification of resources based on the UNFC.

The second reason to link MFA with other methods for meso and macro level decision-making is the lack of economic mechanisms in material flow models and the lack of material flows in economic models. For instance, dynamic macro-MFA based on stock-driven models and economy-wide MFA have been established to model scenarios of future material stock and flows but miss important linkages to the economic system. Rebound effects, for instance, might occur due to efficiency improvements that in turn increase total consumption levels and offset environmental and material benefits (Gielen & Moriguchi, 2002; Skelton et al., 2020). The lack of economic mechanisms in MFA models has long been acknowledged in the literature (Kandelàs & van den Bergh, 1997; Mannaaerts, 2000; van den Bergh & Janssen, 2004) but so far not addressed frequently. A further integration and coupling of MFA with macro-economic models could be established such as macro-economic SD models with dynamic SFA (Pfaff et al., 2018) or CGE with MFA (Grames et al., 2019). Establishing such models could also be useful for prospective dynamic material criticality assessments, making such criticality assessments more applicable for decision-making (Ioannidou et al., 2019). PE or ABS, for instance, have been used to include behavior elements in MFA models and explore future dynamics in metal supply chains (Pothen, 2013; Riddle et al., 2015, 2020).

From a complementary point of view, the material aspect in existing macro-economic models and energy system optimization or integrated assessment models (IAM) are underdeveloped (Kullmann et al., 2021; McCarthy et al., 2018; Pauliuk et al., 2017; Winning et al., 2017). Such models typically do not include material flows and stocks (e.g., material cycles and recycling are typically not included) and if so, are not described in a detailed way. Integrating MFA into macro-economic models is therefore an important step to include materials into these models while improving the economic aspects of stand-alone MFA. An important further step in this regard is to go beyond soft-linked models based on the exchange of data whereby outputs of MFA or macro-economic and IAM models are used as input. Instead, endogenising material flows into the model (making it part of the model such as primary and secondary materials availability as part of the optimization constraints) could provide new insights as illustrated by Huang and Eckelman (2020) and Seck et al. (2020). However, lack of open access to IAMs, including access to data and documentation (Huppmann et al., 2019), is a key limitation for using these models. Improving the accessibility and documentation is therefore important to establish clear
linkages between MFA and the macro-economic models. In addition, alliances with the field of economics (including mineral, ecological, environmental, resource, and IO economics) are another important linkage that should be further established to improve the policy relevance of MFA research (Manderson & Considine, 2018).

5 | CONCLUSIONS

Integrated MFA can inform decision makers to improve the sustainability of material systems. This study has identified the following purposes of integrated MFA: (1) To include economic, social and environmental layers; (2) to evaluate the physical quality and limitations of ME strategies (based on the second law of thermodynamics); (3) to include economic mechanisms and link the economic system to the material system; and (4) to improve the representation of materials in existing methods and models. Implementing integrated MFA requires further collaborations of MFA researchers and practitioners across different areas of expertise to enable a further integration of different tools and data. Collaboration and use of methods from chemical and process (system) engineering is required to improve the data aspect of MFA models and provide a more technical detail essential for material-efficient process and product design and planning. Other disciplines like Operations Research (OR) and OR methods can also provide useful information to establish more relevant MFA models on a company and supply chain level that can feed into the decision-making process. Similarly, the field of economics needs to be further integrated into MFA as this will improve its relevance for policy-making. Finally, an expanded integration of MFA into the LSCA framework could be established to increase collaboration between the two related, but often distinct communities of research and practice. Overall, from our research reported here, it is clear that integrated MFA should be a central method in planning and designing ME strategies for companies and governments.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT
The data that supports the findings of this study are available in the supporting information of this article.

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REFERENCES
Alvandi, S., Bienert, G., Li, W., & Kara, S. (2015). Hierarchical modelling of complex material and energy flow in manufacturing systems. Procedia CIRP, 29, 92–97. https://doi.org/10.1016/j.procir.2015.01.023
Augiseau, V., & Barles, S. (2017). Studying construction materials flows and stock: A review. Resources, Conservation and Recycling, 123, 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002
Ayres, R. U. (1995). Life cycle analysis: A critique. Resources, Conservation and Recycling, 14(3–4), 199–223. https://doi.org/10.1016/0921-3449(95)00017-D
Baccini, P., & Brunner, P. H. (2012). Metabolism of the anthroposphere: Analysis, evaluation, design. MIT Press.
Bartie, N. J., Cobos-Becerra, Y. L., Fröhling, M., Schlatmann, R., & Reuter, M. A. (2021). The resources, exergetic and environmental footprint of the silicon photovoltaic circular economy: Assessment and opportunities. Resources, Conservation and Recycling, 169, 105516. https://doi.org/10.1016/j.resconrec.2021.105516
Beaussier, T., Cauria, S., Bellon-Maurel, V., & Loiseau, E. (2019). Coupling economic models and environmental assessment methods to support regional policies: A critical review. Journal of Cleaner Production, 216, 408–421. https://doi.org/10.1016/j.jclepro.2019.01.020
Bierer, A., Götzé, U., Meynerts, L., & Sygulla, R. (2015). Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. Journal of Cleaner Production, 108, 1289–1301. https://doi.org/10.1016/j.jclepro.2014.08.036
Binder, C. R. (2007). From material flow analysis to material flow management Part I: Social sciences modeling approaches coupled to MFA. Journal of Cleaner Production, 15(17), 1596–1604. https://doi.org/10.1016/j.jclepro.2006.08.006
Blass, V., & Corbett, C. J. (2018). Same supply chain, different models: Integrating perspectives from life cycle assessment and supply chain management. Journal of Industrial Ecology, 22(1), 18–30. https://doi.org/10.1111/jiec.12550
Bleicher, A., & Pehlken, A. (2020). The material basis of energy transitions—An introduction. In A. Bleicher & A. Pehlken (Eds.), The material basis of energy transitions (pp. 1–9). Elsevier.
Bleischwitz, R. (2010). International economics of resource productivity—Relevance, measurement, empirical trends, innovation, resource policies. International Economics and Economic Policy, 7(2–3), 227–244. https://doi.org/10.1007/s10368-010-0170-z
Bode, A., Bürkle, J., Hoffner, B., & Wünsniowski, T. (2012). Looking at the cost: Using flow analysis to assess and improve chemical production processes. Chemical Engineering & Technology, 35(8), 1504–1514. https://doi.org/10.1002/ceat.201200046
Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., & Sonnemann, G. (2021). Co-producing material circularity and independence in the U.S. steel sector. Journal of Cleaner Production, 288, 125053. https://doi.org/10.1016/j.jclepro.2021.125053

Charpentier Poncelet, A., Loubet, P., Laratte, B., Muller, S., Villeneuve, J., & Sonnemann, G. (2019). A necessary step forward for proper non-energetic abiotic resource use consideration in life cycle assessment: The functional dissipation approach using dynamic material flow analysis data. Resources, Conservation and Recycling, 151, 1–10. https://doi.org/10.1016/j.resconrec.2019.104449

Chen, W. Q., & Graedel, T. E. (2012). Anthropogenic cycles of the elements: A critical review. Environmental Science & Technology, 46(16), 8574–8586. https://doi.org/10.1021/es3031033

Choi, C. H., Cao, J., & Zhao, F. (2016). System dynamics modeling of indium material flows under wide deployment of clean energy technologies. Resources, Conservation and Recycling, 114, 59–71. https://doi.org/10.1016/j.resconrec.2016.04.012

Christ, K. L., & Burritt, R. L. (2015). Material flow cost accounting: A review and agenda for future research. Journal of Cleaner Production, 108, 1378–1389. https://doi.org/10.1016/j.jclepro.2014.09.005

Cobo, S., Levis, J. W., Domínguez-Ramos, A., & Irabien, A. (2019). Economics of enhancing nutrient circularity in an organic waste valorization system. Environmental Science & Technology, 53(11), 6123–6132. https://doi.org/10.1021/acs.est.8b06035

Cooper, D. R., Ryan, N. A., Syndergaard, K., & Zhu, Y. (2020). The potential for material circularity and independence in the U.S. steel sector. Journal of Industrial Ecology, 24(4), 748–762. https://doi.org/10.1111/jiec.12971

Daniels, P. L., & Moore, S. (2001). Approaches for quantifying the metabolism of physical economies: Part I: Methodological overview. Journal of Industrial Ecology, 5(4), 69–93. https://doi.org/10.1080/10881980160084042

de Haes, H. U., Heijungs, R., Huppes, G., van der Voet, E., & Hettelings, J.-P. (2000). Full mode and attribution mode in environmental analysis. Journal of Industrial Ecology, 4(1), 45–56. https://doi.org/10.1080/108819800569285

de Kraker, J., Kujawa-Roeleveld, K. J., Villena, M., & Pabón-Pereira, C. (2019). Decentralized valorization of residual flows as an alternative to the traditional urban waste management system: The case of Peñalolén in Santiago de Chile. Sustainability, 11(22), 1–26. https://doi.org/10.3390/su11122606

De Meester, S., Nachtergaele, P., Debaveye, S., Vos, P., & Dewulf, J. (2019). Using material flow analysis and life cycle assessment in decision support: A case study on WEEE valorization in Belgium. Resources, Conservation and Recycling, 142, 1–9. https://doi.org/10.1016/j.resconrec.2018.10.015

Denz, N., Ausberg, L., Bruns, M., & Viere, T. (2014). Supporting resource efficiency in chemical industries—IT-based integration of flow sheet simulation and material flow analysis. Procedia CIRP, 15, 537–542. https://doi.org/10.1016/j.procir.2014.06.060

Dong, D., van Oers, L., Tukker, A., & van der Voet, E. (2020). Assessing the future environmental impacts of copper production in China: Implications of the energy transition. Journal of Cleaner Production, 274, https://doi.org/10.1016/j.jclepro.2020.122825

Dunuwila, P., Rodrigo, V. H. L., & Goto, N. (2020). Improving financial and environmental sustainability in concentrated latex manufacture. Journal of Cleaner Production, 255, https://doi.org/10.1016/j.jclepro.2020.120202

Edgar, T. F., & Pistikopoulos, E. N. (2018). Smart manufacturing and energy systems. Computers & Chemical Engineering, 114, 130–144. https://doi.org/10.1016/j.compchemeng.2017.10.027

Ekins, P., Pollitt, H., Summerton, P., & Chewpreecha, U. (2012). Increasing carbon and material productivity through environmental tax reform. Energy Policy, 42, 365–376. https://doi.org/10.1016/j.enpol.2011.11.094

Fernandez-Mena, H., Gaudou, B., Pellerin, S., MacDonald, G. K., & Nesme, T. (2020). Flows in Agro-food Networks (FAN): An agent-based model to simulate local agricultural material flows. Agricultural Systems, 180, https://doi.org/10.1016/j.agsy.2019.102718

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools—An overview. Journal of Cleaner Production, 13(12), 1165–1173. https://doi.org/10.1016/j.jclepro.2004.06.004

Flachenecker, F., Bleischwitz, R., & Rentschler, J. E. (2017). Investments in material efficiency: The introduction and application of a comprehensive cost–benefit framework. Journal of Environmental Economics and Policy, 6(2), 107–120. https://doi.org/10.1016/j.jenpol.2016.11.094

Fröhling, M., Schwaderer, F., Bartusch, H., & Schultmann, F. (2012). A material flow-based approach to enhance resource efficiency in production and recycling networks. Journal of Industrial Ecology, 17(1), 5–19. https://doi.org/10.1111/j.1530-9290.2012.00502.x

Gao, C., Gao, C., Song, K., & Fang, K. (2020). Pathways towards regional circular economy evaluated using material flow analysis and system dynamics. Resources, Conservation and Recycling, 154, 104527. https://doi.org/10.1016/j.resconrec.2019.104527

Gao, J., & You, F. (2018). Dynamic material flow analysis-based life cycle optimization framework and application to sustainable design of shale gas energy systems. ACS Sustainable Chemistry & Engineering, 6(9), 11734–11752. https://doi.org/10.1021/acssuschemeng.8b01983

Gaustad, G., Krystofik, M., Bustamante, M., & Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. Resources, Conservation and Recycling, 135, 23–33. https://doi.org/10.1016/j.resconrec.2017.08.002

Gaustad, G., Olivetti, E., & Kirchain, R. (2011). Toward sustainable material usage: Evaluating the importance of market motivated agency in modeling material flows. Environmental Science & Technology, 45(9), 4110–4117. https://doi.org/10.1021/es103508u

Gielen, D., & Moriguchi, Y. (2002). Modelling of materials policies. Environmental Modeling & Assessment, 7(4), 231–241. https://doi.org/10.1023/A:1020962804172
Lambrecht, H., & Thilén, N. (2015). Enhancing sustainable production by the combined use of material flow analysis and mathematical programming. Journal of Cleaner Production, 105, 263–274. https://doi.org/10.1016/j.jclepro.2014.07.053

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehler, C. (2019). Taking stock of built environment stock studies: Progress and prospects. Environmental Science & Technology, 53(15), 8499–8515. https://doi.org/10.1021/acs.est.8b06652

Laner, D., & Rechberger, H. (2007). Treatment of cooling appliances: Interrelations between environmental protection, resource conservation, and recovery rates. Resources, Conservation and Recycling, 52(1), 126–155. https://doi.org/10.1016/j.resconrec.2007.03.004

Laner, D., Zoboli, O., & Rechberger, H. (2017). Statistical entropy analysis to evaluate resource efficiency: Phosphorus use in Austria. Ecological Indicators, 83, 232–242. https://doi.org/10.1016/j.ecolind.2017.07.060

Lausselet, C., Urrego, J. P. F., Resch, E., & Brattebø, H. (2020). Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. Journal of Industrial Ecology, https://doi.org/10.1111/jiec.13049

Lenglet, J., Courtonne, J.-Y., & Caurla, S. (2017). Material flow analysis of the forest-wood supply chain: A consequential approach for log export policies in France. Journal of Cleaner Production, 165, 1296–1305. https://doi.org/10.1016/j.jclepro.2017.07.177

Lessard, J.-M., Habert, G., Tagnit-Hamou, A., & Amor, B. (2021). A time-series material-product chain model extended to a multiregional industrial symbiosis: The case of material circularity in the cement sector. Ecological Economics, 179, https://doi.org/10.1016/j.ecolecon.2020.106872

Levik, A. N., Modaresi, R., & Müller, D. B. (2014). Long-term strategies for increased recycling of automotive aluminum and its alloying elements. Environmental Science & Technology, 48(7), 4257–4265. https://doi.org/10.1021/es500820h

Manderson, E. J., & Considine, T. J. (2018). An economic perspective on industrial ecology. Review of Environmental Economics and Policy, 12(2), 304–323. https://doi.org/10.1093/reep/rey001

Mannaerts, H. (2000). STREAM: Substance Throughout Related to Economic Activity Model: A partial equilibrium model for material flows in the economy. CPB Netherlands Bureau for Economic Policy Analysis. https://www.cpb.nl/en/publication/stream-substance-throughput-related-economic-activity-model-partial-equilibrium-model

Marwedel, M., & Reller, A. (2014). Estimation of life cycle material costs of cadmium telluride- and copper indium gallium diselenide-photovoltaic absorber materials based on life cycle material flows. Journal of Industrial Ecology, 18(2), 254–267. https://doi.org/10.1111/jiec.12108

Masanet, E., Heeren, N., Kagawa, S., Cullen, J., Lifset, R., & Wood, R. (2021). Material efficiency for climate change mitigation. Journal of Industrial Ecology, 25(2), 254–259. https://doi.org/10.1111/jiec.13137

May, N., & Guenther, E. (2020). Shared benefit by Material Flow Cost Accounting in the food supply chain—The case of berry pomace as upcycled by-product of a black currant juice production. Journal of Cleaner Production, 245, https://doi.org/10.1016/j.jclepro.2019.118946

McCarthy, A., Dellink, R., & Bibas, R. (2018). The macroeconomics of the circular economy transition. [Environment working papers No. 130]. https://www.oecd-ilibrary.org/docserver/af983f9a-en.pdf?expires=1627288267&id=id&accname=guest&checksum=D80C200E34B48914223AD811B04236CF

Meglin, R., Kytzia, S., & Habert, G. (2021). Regional circular economy of building materials: Environmental and economic assessment combining material flow analysis, input-output analyses, and life cycle assessment. Journal of Industrial Ecology, https://doi.org/10.1016/j.jiec.13205

Mehr, J., Vandenbo, C., Steubing, B., & Hellweg, S. (2018). Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades. Resources, Conservation and Recycling, 131, 181–191. https://doi.org/10.1016/j.resconrec.2017.12.026

Meyer, B., & Lutz, C. (2007). The Ginfors model: Model overview and evaluation. [http://www.petre.org.uk/pdf/sept08/petre_WP%2020%20Ginfors.pdf]

Michaels, P., & Jackson, T. (2000). Material and energy flow through the UK iron and steel sector: Part 2: 1994–2019. Resources, Conservation and Recycling, 29(3), 209–230. https://doi.org/10.1016/S0921-3449(00)00041-0

Michalkakis, C., & Cullen, J. M. (2021). Dynamic exergy analysis: From industrial data to exergy flows. Journal of Industrial Ecology, 26(1), 12–26. https://doi.org/10.1111/jiec.13168

Moeller, A., Prox, M., Schmidt, M., & Lambrecht, H. (2010). Simulation and optimization of material and energy flow systems. Proceedings—Winter Simulation Conference, 2009, 1444–1455. https://doi.org/10.1109/WSC.2009.5429229

Müller, D., Lundhag, M., & Simoni, M. (2018). Challenges, systems and data. (Synthesis report. MinFuture project deliverable D2.2). https://minfuture.eu/D2_2.html

Müller, E., Hilty, L. M., Widmer, R., Schluep, M., & Faulstich, M. (2014). Modeling metal stocks and flows: A review of dynamic material flow analysis methods. Environmental Science & Technology, 48(4), 2102–2113. https://doi.org/10.1021/es403506a

Müller, M. (2013). Developing a method for economic and ecologic optimization of manufacturing processes based on material flow analysis (MFA). Vienna University of Technology.

Nakamura, S., & Kondo, Y. (2018). Toward an integrated model of the circular economy: Dynamic waste input–output. Resources, Conservation and Recycling, 139, 326–332. https://doi.org/10.1016/j.resconrec.2018.07.016

Nakamura, S., Kondo, Y., Kagawa, S., Matsuue, K., Nakajima, K., & Nagasaka, T. (2014). MaTrace: Tracing the fate of materials over time and across products in open-loop recycling. Environmental Science & Technology, 48(13), 7207–7214. https://doi.org/10.1021/es500820h

Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., & Pauliuk, S. (2017). Quantifying recycling and losses of Cr and Ni in steel through multiple life cycles using MaTrace-Alloy. Environmental Science & Technology, 51(17), 9469–9476. https://doi.org/10.1021/acs.est.7b01683

Nuss, P., Graedel, T. E., Alonso, E., & Carroll, A. (2016). Mapping supply chain risk by network analysis of product platforms. Sustainable Materials and Technologies, 10, 14–22. https://doi.org/10.1016/j.susmat.2016.10.002

Obrist, M. D., Kannan, R., Schmidt, T. J., & Kober, T. (2021). Decarbonization pathways of the Swiss cement industry towards net zero emissions. Journal of Cleaner Production, 288, https://doi.org/10.1016/j.jclepro.2020.125413

OECD. (2008). Measuring material flows and resource productivity. Organization for Economic Cooperation and Development.

OECD. (2020). The circular economy in cities and regions: Synthesis report. [https://www.oecd.org/regional/the-circular-economy-in-cities-and-regions-10ac6ae4-en.htm]

Ohno, H., Matsuue, K., Nakajima, K., Kondo, Y., Nakamura, S., Fukushima, Y., & Nagasaka, T. (2017). Optimal recycling of steel scrap and alloying elements: Input–output based linear programming method with its application to end-of-life vehicles in Japan. Environmental Science & Technology, 51(22), 13086–13094. https://doi.org/10.1021/acs.est.7b04477

Olivetti, E., Field, F., & Kirchain, R. (2015). Understanding dynamic availability risk of critical materials: The role and evolution of market analysis and modeling. MRS Energy & Sustainability, 2, 1–16.
Yang, F., & Liu, Y. (2016). Evaluation and integration of energy utilization in a process system through material flow analysis coupled with exergy flow analysis. Process Safety and Environmental Protection, 103, 334–347. https://doi.org/10.1016/j.psep.2016.03.002

SUPPORTING INFORMATION
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