

Chapter 12

Material Flow Analysis and Waste Management

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Abstract Material flow analysis (MFA, also known as Material Flow Accounting) has become one of the basic tools in industrial ecology, since its pioneering development by Ayres. This chapter reviews progress in MFA with emphasis on the use of MFA to support waste management and recycling policy.

Waste statistics are compiled in most developed and some developing countries, but the basis is insufficiently standardized so that care is needed in making comparisons between countries. This also applies to recycling flows, which are difficult to define and quantify. Waste arising from demolition can be predicted by dynamic modeling which also predicts future resource demand, but the discrepancies between predicted and reported waste quantities can be large due to “missing” or “dissipated” stock. Metals represent an important and valuable component of waste; metals in end-of-life vehicles and e-waste in particular need to be quantified for their recycling and ecological and human health impact assessment. MFA has also been applied to international trade of secondhand products containing metals. MFA studies on phosphorus have revealed potential ways to increase recovery that go beyond recycling from obvious wastes. Analysis of stocks must be an important topic in coming decades.

Policies designed to move the economy towards “circularity” have been promoted in some countries, including China and Japan, as practical manifestations of the industrial ecology paradigm. In China, the link to MFA was only recognized some years after the introduction of the policy, whereas in Japan MFA was accepted from the outset.

Measures are being advocated, for example by the OECD, to improve the comparability of MFA across different data sources. Input-output analysis is increasingly applied to estimate and represent material flows. In general, MFA has matured to the point where it is now mandated as a tool for national and international policy. But further expansion and integration are expected.

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1 Introduction – Historical and Institutional Perspectives

This chapter reviews the recent progress in methodologies and applications of material flow analysis (MFA) with emphasis on waste management and recycling perspective. An overview of the progress of economy-wide MFA can be found in a recent review by Fischer-Kowalski et al. (2011).

Robert Ayres and Allen Kneese presented the first version of what would become MFA of national economies as early as in 1969 (Ayres and Kneese 1969) (see Chap. 1). Ayres subsequently edited two books on resource accounting (Ayres and Ayres 1998, 1999) as well as a handbook of industrial ecology (Ayres and Ayres 2002). The section on MFA of this handbook (Bringezu and Moriguchi 2002) begins with the sentence, “understanding the structure and functioning of the industrial or societal metabolism is at the core of industrial ecology,” followed by the definition that “Material flow analysis (MFA) refers to the analysis of the throughput of process chains comprising extraction or harvest, chemical transformation, manufacturing, consumption, recycling and disposal of materials.” Approaches for quantifying the metabolism of physical economies were comprehensively reviewed by Daniels and his colleagues (Daniels and Moore 2001; Daniels 2002).

Looking back on the last two decades, ConAccount, a network of institutions and experts working on MFA, has played a key role in the progress of MFA (Moriguchi 2007). ConAccount started in May 1996 as a concerted action entitled “Coordination of Regional and National Material Flow Accounting for Environmental Sustainability.” ConAccount convened several times, mainly in Europe. More recently, it was integrated into the International Society of Industrial Ecology (ISIE) as a section, now entitled Socio-Economic Metabolism (SEM) (see also Chap. 6).

In addition to national accounting of material flows, MFA has been increasingly used as a basis for analyzing and planning waste management and recycling systems. By search on the Web of Science (“material flow analysis” and “waste or recycling”), more than 300 articles that used an MFA approach for analyzing waste and recycling issues were found. Publications in these areas started in the late 1990s and the number has gradually increased, to reach more than 50 in 2014. The citations in each year have also increased up to 800 in 2014 with about 11 average citations per article. The number of articles and their citation is expected to expand further. In addition to *Journal of Industrial Ecology*, many articles are found in journals such as *Resources, Conservation and Recycling*, *Environmental Science and Technology*, *Waste Management*, and *Waste Management and Research*.

The following sections review the empirical studies of MFA for waste management and recycling from the viewpoint of target wastes and systems and MFA-

based policies and concepts for sustainable resource and waste management. The chapter goes on to discuss the outlook for possible integration of methodologies and future developments in MFA.

2 Review of Empirical Studies from the Viewpoint of Target Wastes and Systems

2.1 Waste in General

In many developed countries, waste statistics are available (e.g. OECD 2005) as a basis for framing waste management and recycling policy (see Chap. 14). Institutionalization of the compilation of waste statistics is essential for appropriate waste management in developing countries (see Chap. 11). However, one of the issues in waste statistics is that definition and coverage of waste streams (e.g. municipal/industrial, hazardous/non-hazardous) vary considerably across countries. Therefore, comparison of waste indicators needs careful interpretation. The same applies to indicators such as recycling rate.

It is interesting and useful to capture recycling flows as parts of more comprehensive picture of material flows: such flows are accounted for in some national MFAs. However, defining recycling flows is not easy. The first version of the methodological guide for economy-wide MFA (Eurostat 2001) says “Recycling flows are not part of the material balance,” because “First, data on materials recycled within statistical units are not normally available. Second, the definition and measurement of recycling flows is difficult.” In this regard, Hashimoto and Moriguchi (2004) categorized the forms of recycling and proposed alternative indicators that can avoid double-counting and/or inflated recycling flows or rates. Concerning recycling ratio, Graedel et al. (2011) gave definitions of various metrics related to end-of-life recycling. Further, Bailey et al. (2008) proposed input–output cycling metrics that can measure cycling of both direct and indirect flows in a complex system while traditional metrics only account for direct flows. Further discussion and development are needed on the issue of defining and measuring recycle flows.

2.2 Construction and Demolition Waste

A number of MFA studies are available related to construction and demolition waste for countries and regions such as China (Shi et al. 2012; Huang et al. 2013), Japan (Hashimoto et al. 2007, 2009), The Netherlands (Müller 2006), Norway (Bergsdal et al. 2007), and Taiwan (Hsiao et al. 2002); for cities such as Beijing (Hu, D. et al. 2010; Hu, M. et al. 2010); and for specific infrastructures such as highway traffic system (Wen and Li 2010).

The dynamic model presented by Müller (2006) is now often used to estimate future resource demand and waste generation. The feature of this model is that service provided by stocks, determined by population and lifestyle, is the driver of future service demand and related resource demand (see Chaps. 6 and 7). This is a reasonable assumption when we want to foresee long-term trends of material flows.

Modeling future demolition waste generation is one objective of these MFA studies. However, Hashimoto et al. (2007) showed that there can be very large discrepancies between the amounts estimated in the studies and the statistical quantities reported. One possible reason is that considerable amounts of construction materials do not emerge as wastes. Hashimoto et al. (2007) referred to this as “missing stock” or “dissipated stock” and then proposed a framework for estimating potential wastes accumulated within an economy (Hashimoto et al. 2009). Materials input into an economy include dissipatively used materials, such as crushed stone used for leveling the ground and reclaiming ground, and permanent structures, such as tunnels and dams with a low probability of being demolished. This point should be considered when we model future generation of demolition waste and its recyclability.

Demolition waste is also important from the viewpoint of disaster waste management because it is a major portion of the waste to be managed following a disaster. Tanikawa et al. (2014) estimated such waste as “lost material stock,” taking the great east Japan earthquake as a case study. Methodological development for quickly estimating the amount of disaster waste is important for the IE community, because planning waste management and recycling is one of the first steps for recovery from disaster.

2.3 *End-of-Life Vehicles and e-Waste*

End-of-life vehicles contain many valuable materials that should be recovered (see Chap. 18). An objective of MFA studies is, therefore, to capture flows of resources contained in end-of-life vehicles, such as aluminum (Cheah et al. 2009; Mathieux and Brissaud 2010; Modaresi and Müller 2012; Hatayama et al. 2012), steel, copper, lead, and zinc (Fuse et al. 2009; Yano et al. 2014). Further, Richa et al. (2014) analyzed lithium-ion battery waste flows from electric vehicles in the future.

Material flows of e-waste have been studied in many countries to support its management and recycling, e.g. Brazil (Araújo et al. 2012), China (Liu et al. 2006; Yang et al. 2008; Chung 2012; Zhang et al. 2012; Habuer et al. 2014; Li et al. 2015), Chile (Steubing et al. 2010), Czech Republic (Polak and Drapalova 2012), Germany (Walk 2009), Hong Kong (Chung et al. 2011; Lau et al. 2013), India (Dwivedy and Mittal 2010a, b), Indonesia (Andarani and Goto 2014), Iran (Rahmani et al. 2014; Alavi et al. 2015), Japan (Yamasue et al. 2007; Oguchi et al. 2008; Yoshida et al. 2009), Nigeria (Osibanjo and Nnorom 2008; Nnorom and Osibanjo 2008), South Korea (Lee et al. 2007; Kim et al. 2013), Spain (Gutierrez et al. 2010), USA (Kang and Schoenung 2006; Leigh et al. 2007; Kahhat and Williams 2012; Lam et al.

2013; Schumacher et al. 2014), and in the global economy (Yu et al. 2010). Some studies have estimated flows of specific materials contained in e-waste such as steel, aluminum, copper, lead, nickel, and zinc (Yamasue et al. 2007; Lam et al. 2013; Habuer et al. 2014) and parts such as lithium-ion batteries (Chang et al., 2009). Tracking international trade of second-hand e-products is another research objective of MFA to assess the potential negative impacts on the environment in importing countries (Kahhat and Williams 2009, 2012; Yoshida and Terazono 2010; Breivik et al. 2014).

In many countries, data on e-products and e-waste are limited. Further, consumers tend to store old e-products at home even if they are no longer used. Therefore, methodological aspects for estimating e-waste flows have been discussed (Leigh et al. 2007; Yoshida et al. 2009; Gutierrez et al., 2010; Araújo et al. 2012; Wang et al. 2013; Li et al. 2015). Moreover, Lam et al. (2013) combined MFA with ecological and human health impact assessment caused by heavy metals in e-waste. Metals in end-of-life vehicles and e-waste need to be quantified for planning recycling and assessing risks. Streicher-Porte et al. (2009) integrated MFA, life cycle assessment (LCA), and multiple attribute utility theory to evaluate scenarios for computer supplies to schools in Colombia. These methodological developments and integration of different tools are important next steps for MFAs.

2.4 *Metals in Waste*

There is a substantial body of research related to metal flows and stocks (Chen and Graedel 2012), inevitably including waste and recycling flows.

One of the motivations of metal flow studies is to estimate recycling rates of those metals. Graedel et al. (2011) provide an overview on the current knowledge of recycling rates for 60 metals and show that many end-of-life recycling ratios (EOL-RRs) are very low: only for 18 metals (silver, aluminum, gold, cobalt, chromium, copper, iron, manganese, niobium, nickel, lead, palladium, platinum, rhenium, rhodium, tin, titanium, and zinc) is the EOL-RR above 50 % at present. We need further research on recycling flows; this should be standardized and institutionalized in the compilation of statistics.

How many times materials are expected to be recycled is also an interesting and important question (see Chap. 7). Markov chain modeling has been applied to estimate average times of use of steel (Matsuno et al. 2007), stainless steel (Hashimoto et al. 2010), nickel (Eckelman et al. 2012), and copper (Eckelman and Daigo 2008). Results were, respectively, 2.7, 1.9–4.3, 3, and 1.9 times.

Some studies discuss alloying elements in metal recycling (Nakajima et al. 2011, 2013; Nakamura et al. 2012; Ohno et al. 2014). For example, Ohno et al. (2014) showed that considerable amounts of alloying elements, which correspond to 7–8 % of the annual consumption in electric arc furnace (EAF) steelmaking, are unintentionally introduced into EAFs. This type of analysis is an interesting application of MFA to help development of more appropriate recycling systems.

As metal stocks in a society are important sources of secondary resources, research related to the assessment of stocks has been increasing (Gerst and Graedel 2008). Using satellite night-time light observation data is an innovative and interesting methodological approach to stock estimation (Takahashi et al. 2009; Hsu et al. 2013). On the conceptual aspect of stocks as resources, classification of secondary resources in the anthroposphere was proposed (Hashimoto et al. 2008), based on the classification of primary resources in the lithosphere, i.e. so-called McKelvey diagram (McKelvey 1972). Analysis of stocks must be an important topic in coming decades.

2.5 *Phosphorus in Waste*

Phosphorus is as an essential nutrient for agriculture, but phosphate rock is a non-renewable resource and its deposits will be exhausted in a long term. Therefore, in addition to increasing phosphorus use efficiency in agricultural systems, phosphorus needs to be recovered from all current waste streams (Cordell et al. 2011). Especially, wastes rich in phosphorus can represent new sources. MFA can provide an effective tool to identify such new sources.

Sewage sludge is one candidate as a potential source of phosphorus and commonly utilized by spreading directly to farm land (Lederer and Rechberger 2010). However, by conducting MFA of phosphorous in Gothenburg, Sweden, Kalmykova et al. (2012) concluded that solid waste incineration residues represented a large underestimated sink of phosphorus and that focusing on wastewater as the sole source of recovered phosphorus was not sufficient. Further, Matsubae-Yokoyama et al. (2009) analyzed availability of phosphorus resources that remain untapped for Japan and found that the quantity of phosphorus in iron and steel-making slag was almost equivalent to that in imported phosphate ore in terms of both amount and concentration.

2.6 *Waste Plastics*

Attention has been paid to the management of waste plastics. MFAs have been carried out for different types of plastics in many countries, e.g. plastics streams in general in Austria and Poland (Bogucka et al. 2008), in Germany (Patel et al. 1998), in India (Mutha et al. 2006), in the Netherlands (Joosten et al. 2000) and in Serbia (Vujic et al. 2010); for polyethylene terephthalate flows in Colombia (Rochat et al. 2013) and in the US (Kuczenski and Geyer 2010); flows of polyvinyl chloride in

China (Zhou et al. 2013), in Japan (Nakamura et al. 2009), and in Sweden (Tukker et al. 1997; Kleijn et al. 2000); and flows of waste tires in China (Yang et al. 2010), Thailand (Jacob et al. 2014) and in small island developing states (Sarkar et al. 2011).

Implementing MFA of plastics is not easy because many plastics, such as polyethylene and polypropylene, are used in a variety of products, from construction to consumer products, whose lifetimes are different. Therefore, input-output analysis has been applied to estimate flows of plastics (Joosten et al. 2000; Nakamura et al. 2009; Yang et al. 2010).

2.7 *Spatial System Boundaries*

Amongst the body of studies targeting countries and cities are a number with interesting system boundaries.

For example, many islands face waste issues because of their limited availability of land for waste disposal as well as constrained availability of physical material resources. Therefore, research on waste flows has been performed for some small island states (Eckelman and Chertow 2009; Sarkar et al. 2011; Eckelman et al. 2014). An island is also a useful system for industrial ecology studies as it is a valuable unit of study for biological sciences (Deschenes and Chertow 2004).

Industrial ecosystems are another example, where one company's waste becomes another company's feedstock. Many studies have been undertaken in the field of industrial symbiosis research (see Chap. 5). For example, Lyons (2007) examined the issue of geographic scale and loop closing for heterogeneous wastes through an analysis of the location and materials flows of a set of recycling, remanufacturing, and waste treatment firms in Texas and showed that there was no preferable scale at which loop closing should be organized.

A process of waste treatment can also be the subject of MFA. For example, Chancerel et al. (2009) assessed precious metal flows during preprocessing of waste electrical and electronic equipment and showed that only 11.5 % of the silver and 25.6 % of the gold and of the palladium reach output fractions from which they can potentially be recovered.

International transfer of e-waste has been a major concern. Therefore, MFA has also been applied to international trade of secondhand products (Kahhat and Williams 2009, 2012; Yoshida and Terazono 2010; Breivik et al. 2014). Such trade can be seen as the trade of metals contained in the products. Fuse et al. (2009) estimated global flows of metal resources in the used automobile trade.

3 MFA-Based Policies and Concepts for Sustainable Resource and Waste Management

3.1 *Conceptual Progress for Sustainable Resource and Waste Management and Its Relevance to MFA – Cases in China and Japan*

According to Yuan et al. (2006), the circular economy (CE) was first proposed as a concept by scholars in China in the 1990s, and subsequently formally adopted in 2002 by the central government as a new development strategy. Yuan et al. (2006) state that the CE concept originates from the industrial ecology paradigm, building on the notion of loop-closing emphasized in German and Swedish environmental policy. According to another article on industrial ecology research in China (Shi et al. 2002), the first time that the term “industrial ecology” appeared in a Chinese academic publication was in 1990, published by Tsinghua University Press. Most recently, the CE was adopted as a keyword to promote resource efficiency policy in Europe. In summer 2014, the European Commission adopted the Communication “Towards a circular economy: a zero waste program for Europe” to establish an EU framework to promote the circular economy. Chap. 7 explores the different concepts brought together under the heading “circular economy.”

Shi et al. (2002) also reviewed the state of research on and practice of core constituents of industrial ecology: LCA, DfE, MFA, EIPs, and closed-loop economies. They found that the wide gap between LCA application and policy making needed to be filled and, as compared to LCA, MFA was even less developed in China, as of early 2000s. Thus MFA was not explicitly linked to CE in China, at least in the early stage of the policy.

Earlier in 2000 in Japan, a new fundamental law towards “Jun-kan” (circular) society was adopted. The initial official translation of the circular society was “recycling-based society” but this was subsequently revised to “sound material-cycle (SMC) society.” “Jun-kan” in Japanese and “XÚNHUÁN” in Chinese are synonymous, both of them meaning “circulation.” Japan’s preliminary economy-wide MFA can be found in a report by a committee organized by the Environment Agency in 1991 to examine the “Jun-kan” socio-system (Hashimoto 2009). Here, a similar phrase to “Jun-kan” society appeared for the first time in Japan’s environmental administration. MFA and the circular society concept, therefore, have close relations for Japan.

A review by Takiguchi and Takemoto (2008) confirmed that the framework of 3Rs (reduce, reuse, and recycle) policies to establish a SMC Society was designed on the basis of research on MFA. A set of three economy-wide MF indicators was introduced into the Fundamental Plan for SMC Society in 2003, and numerical targets were set for each indicator. The concept of the 3Rs by Japan was also shared on a global scale through the Group of Eight (G8) process known as the 3R Initiative.

3.2 Initiatives in National and Intergovernmental Activities, Focusing on Policy Application of Economy-Wide MFA Indicators

Institutional aspects of progress in international MFA studies were reviewed by Moriguchi (2007), focusing on developments in Japan and in international fora such as within the Organisation for Economic Cooperation and Development (OECD). Experts in industrial ecology, including the authors of this chapter themselves, have played catalytic role in linking industrial ecology studies and their applications to national and international policies for sustainable resource and waste management. A typical example of the outcomes from these international activities is the OECD three-volume guidelines focusing on economy-wide MFA (OECD 2008), published when OECD and UNEP coorganized a Conference on Resource Efficiency in 2008.

Fischer-Kowalski et al. (2011) reviewed the state-of-the-art and reliability of MFA data across different sources. They concluded that the MFA framework and the data generated have reached a maturity that warrants MF indicators to complement traditional economic and demographic information in providing a sound basis for discussing national and international policies for sustainable resource use. International comparison of a few economy-wide MFA indicators (Bringezu et al. 2004), cross country comparisons of economy-wide MFA within the EU (Weisz et al. 2006) as well as country case studies such as in an EU accession country (Kovanda et al. 2010) have been conducted. There has been much criticism against using simplistic summation of different materials by mass as an indicator. Van der Voet et al. (2005) added a set of environmental weights to the flows of the materials to calculate indicators with differentiated environmental impact. Another key argument is accounting for indirect material requirement associated with processed materials and products. The “raw material equivalents” (RME) metric of material consumption addresses the issue of including the full supply chain (including imports) when calculating national or product level material impacts (Muñoz et al. 2009; Schor et al. 2013).

Aoki-Suzuki et al. (2012) conducted a study of how economy-wide MFA indicators are used in a number of developed countries, including analysis of the commonalities between countries that are actively using these indicators in policy, and a survey of the current capacity for economy-wide MFA in developing countries, including data availability and policy uptake.

4 Current and Future Developments

In parallel with the remarkable progress of empirical MFA studies in industrial ecology, there have been developments in statistical institutionalization of physical accounting as well as methodological elaboration employing Input-Output Tables. SEEA 2003 (System of integrated Environmental-Economic Accounting, 2003

edition) pays considerable attention to physical flow accounting, in addition to natural resource stock accounts and environmental protection expenditure accounts, and introduced the National Accounting Matrix including Environmental Accounts (NAMEA) as one of the main building blocks (Pedersen and de Haan 2006). Accounting framework was also discussed in one of the three volumes of OECD's MFA guidance in 2008. Under the Regulation (EU) 691/2011 on European environmental economic accounts, Eurostat collects economy-wide MFA from the national statistical institutes of the EU Member States.

Environmental extension of economic Input-Output Tables (IOT) has been undertaken both by experts in Input-Output analysis and by users of this approach (see Chap. 8). IOT describes intersectoral monetary flows, but this approach can provide a consistent framework to describe the physical balance of inflows and outflows. Wastes have conventionally not been included in monetary IOT (MIOT) because of their negative economic value. Attempts were made to include waste flows by physical IOT (PIOT) (Dietzenbacher 2005) and consistency between MIOT and PIOT was discussed (Weisz and Duchin 2006). A new framework designed specifically for the analysis of waste issues was developed by Nakamura and Kondo (2002), and they and their colleagues published a number of studies on framework and applications of Waste Input Output (WIO) tables (Nakamura et al. 2007, 2008, 2009). Lenzen and Reynolds (2010) applied a "supply and use" framework to WIO and confirmed the consistency between their Waste Supply-Use Tables (WSUT) and WIO. Recently, empirical studies of PIOT at local levels in China were reported by Liang and Zhang (2011).

Literally, MFA analyses flows of materials. However, there is no reason to restrict the scope of MFA within this definition. MFA is a general system approach that can be used to explore various interfaces between

- Flows and stocks
- Technosphere and ecosphere
- Upstream resource issues and downstream waste issue
- Valuable materials and toxic substances
- Energy (with GHGs) and materials (from non-renewables)
- Theoretical analysis/models and on-site practices
- Scientific studies and policy applications

so as to understand and improve socio-economic metabolism. Further, integration of other methodologies such as IO analysis, LCA, risk assessment, environmental impact assessment, and technology assessment are expected.

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