Chapter 11
Closing the Loop: Industrial Ecology, Circular Economy and Material Flow Analysis

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Abstract This chapter explores the principles supporting industrial ecology (IE), circular economy (CE) and material flow analysis (MFA). IE concerns constructing industrial and societal processes according to ecological principles. One of the main features within IE is the principle of closing material loops by avoiding pollution. Insights from IE further aid in building the understanding essential for establishing the principles of circularity in the resource economy. MFA is viewed as an analytical method rooted in the field of IE and Systems Engineering (SE).

11.1 Industrial Ecology

According to Graedel (1996), Industrial Ecology (IE) should be defined as follows:

> Industrial ecology is the study of the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal.

This definition is based on a systems' view and nature's carrying capacity. However, there are several definitions of IE (O'Rourke et al. 1996) which consider other objectives such as closed material cycles, evolutionary principles, resiliency, dynamic feedback, cooperation and competition in ecosystems. Industrial Ecology (IE) is the broad umbrella or the framework for thinking about and organizing production and consumption systems in ways that resemble natural ecosystems. This

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A. M. Fet (ed.), *Business Transitions: A Path to Sustainability*,
https://doi.org/10.1007/978-3-031-22245-0_11

idea considers human societies to be part of and operate within natural ecosystems (Ehrenfeld 1994). The basic concept is to model industrial systems on natural ecosystems. IE aims to interpret and adopt an understanding of the natural system and apply it to the design of the man-made system to achieve a pattern of industrialization that is more efficient and adjusted to the tolerances and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them. In contrast to industrial production, the natural environment has evolved into an inherently sustainable, cyclical system over billions of years. IE aims to incorporate these cyclical patterns into sustainable designs for industrial production systems. A pattern of change is illustrated by Fig. 11.1 (Jelinski et al. 1992).

In the early phases of the industrial revolution, the potentially usable resources were significant, and the existence of life forms was minimally impacted by extraction or waste. This view of *unlimited resources* might be described as linear, that is, as one in which the flow of material from one stage to the next is independent of all other flows (Jelinski et al. 1992). A contrasting picture emerges with "limited resources" as an ecosystem view. In such a system, life forms become strongly interlinked and form the complex networks we know today. According to the growing resource scarcity, industrial systems will be increasingly put under pressure to evolve to move from linear to semi-cyclic modes of operation. The central domain of IE is depicted in Fig. 11.1 with four central nodes: the materials extractor or grower, the materials processor or manufacturer, the consumer, and the waste

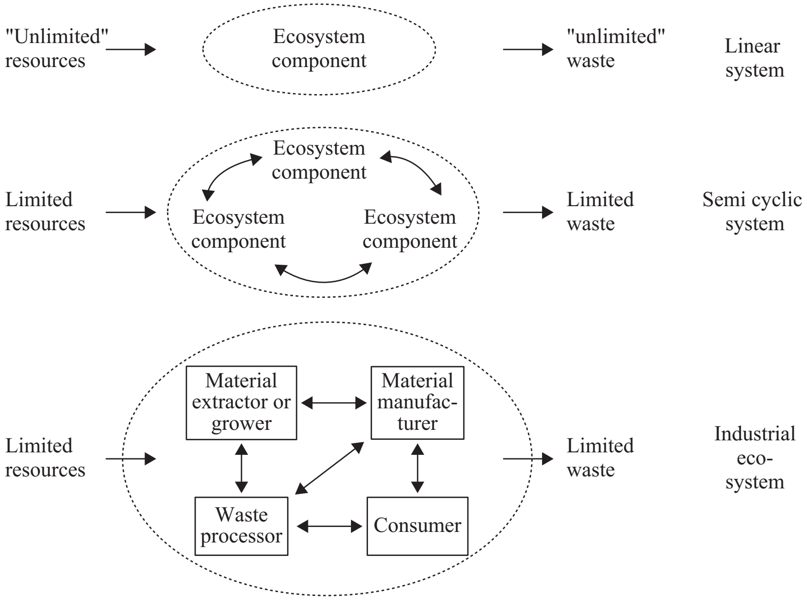

Fig. 11.1 The change from linear to cyclic material flows in the industrial ecosystem

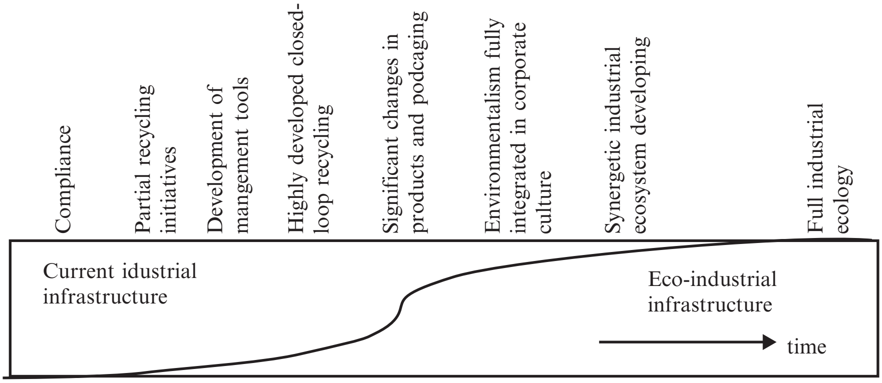

Fig. 11.2 The emergence of an eco-industrial infrastructure (Tibbs 1992)

processor. To the extent that they operate within the nodes in a cyclic manner or organise to encourage the cyclic flow of materials within the entire industrial ecosystem, they evolve into modes of operation that are more efficient and have a less disruptive impact on external support systems. Examples range from recycling of iron scrap by the heavy metals industry to the popularity of garage sales for the reuse of products in the consumer domain (Jelinski et al. 1992).

Applied IE embraces both business applications and technology opportunities (Tibbs 1992). It provides a basis for developing strategic options and policy decisions for those in management. Tools for analysis of the interface between industry and the environment is needed (Fet 2002). On the technical side, IE offers specific engineering and operational programmes for data gathering, technology deployment and product design. The technologies of real-time environmental monitoring are becoming increasingly sophisticated and must be integrated using information technology as a practical tool for mapping and managing environmental impacts. According to Tibbs (1992), process and product design should reflect IE thinking from initial design principles to final decommissioning and disassembly. The emergence of an eco-industrial infrastructure is illustrated by Fig. 11.2, which shows a set of shifts, both technological and institutional. With the goal of bringing industrial development into balance with natural and social systems, the two main objectives are to *achieve closed material cycles* and *realize a fundamental paradigm shift in our thinking about industry-environment relations* (O'Rourke et al. 1996). The first is an urgent goal. Unless product and material cycles are closed, the industrial system will continue to be unsustainable. Regarding the second goal, technology alone cannot achieve the transformation. It must therefore work within societal systems. The fundamental point is that implementation of IE, and over time, migration towards sustainable development will involve significant cultural, societal, and political changes. Resolving these conflicts requires fundamental change to our system of economics. (Tibbs 1992).

11.2 Implementing Industrial Ecology Principles in Business

Implementing IE principles into business practice requires simple rules, such as pollution prevention and material cascading. Material cascading means that waste from one company should be regarded as a resource for another company, which considers waste minimization, resource and energy efficiency and recycling opportunities. Pollution prevention includes re-designing products and processes where efforts like phasing out toxic materials emissions of persistent synthetic materials are essential. Raw material extraction should be reduced, the material should be selected and used with respect to the product life cycle, and material flows should be optimized concerning natural material cycles (Jackson 1993). IE is grounded in holistic life cycle system understanding. Ehrenfeld (1994) presented a list (based on Tibbs 1992) of the seven components of IE which should be considered when implementing IE principles in industry. A modifed version of the list of components is presented in Table 11.1).

The words which are written in cursive are used to highlight the critical issues within each of the categories. Adopting these in business practice relies on the incentives, competence, and willingness to change. In short, it can be said that the implementation of IE principles is about understanding ecological principles on one hand and understanding the interactions between business activity and the impacts on ecological systems on the other.

When implementing IE, process optimization comes first. Integration and coordination between firms are typically a prerequisite and closed-loop systems mean material reuse and recycling within a firm and material and energy cascading between firms. The industry parks Kahlundborg in Denmark and Nova Scotia in Canada are used to demonstrate IE in practice in a special set of relationships known as Industrial Symbiosis (Doménech and Davies 2011).

Table 11.1 Principal characteristics of industrial ecology

	Category
1:	Balancing industrial input and output to natural *ecosystem capacity*, hereunder identifying ways that industry can safely interface with nature in a holistic life cycle perspective.
2:	*Dematerialization* of industrial output, hereunder striving to decrease materials and energy intensity in industrial production.
3:	Creating *loop-closing* industrial practices, hereunder improving the efficiency of industrial processes by re-designing production processes and products for maximum conservation of resources.
4:	Improving *metabolic* pathways for materials use and industrial processes, hereunder create industrial ecosystems by fostering cooperation among various industries whereby the waste of one production process becomes the feedstock for another.
5:	*Systematizing* patterns of energy use, hereunder development of renewable energy supplies for industrial production, and creating energy system that functions as an integral part of industrial ecosystems.
6:	*Aligning policy* to conform with long term industrial system evolution, hereunder adoption of new national and international economic development policies

Modified after Ehrenfeld (1994)

However, there are omissions and weaknesses within IE. Policies often do not support goals, and analyses regarding the problems in changing current industrial practices, are often lacking. One major problem IE is facing is securing safe, clean, abundant alternatives to fossil fuels. Energy flow must remain open in any closed material cycle since energy cannot be recycled. It is of paramount importance, therefore, to switch to renewable energy sources whenever possible. This is not merely a technical issue: it requires structural societal changes such as governments putting forward policies for increasing the use of renewable energy and acceptance and the support of those policies by stakeholders as well as the public.

11.3 Closing the Loop: Circular Economy

The six principal characteristics of Industrial Ecology are presented in Table 11.1. The development of IE has also resulted in the emergence of new concepts such as green engineering, design for sustainability, eco-design, eco-industrial network and the Circular Economy (CE). CE gained traction in policy, business and academia and advocates the transformation of industrial systems from a traditional linear *take-make-dispose* model toward a circular model in which waste is a resource that is valorized through recycling and reuse (Geissdoerfer et al. 2017). For the business sector, three elements of CE provide a suitable means to operationalize sustainable industrial practices as they:

- increase the efficiency of resource utilization, thereby improving competitiveness and profitability (OECD 2021)
- provide an alternative to economic development models (Kirchherr et al. 2017)
- promote environmentally friendly use of resources (MacArthur 2013)

Figure 11.2 shows how elements of IE can be reflected in conceptualizing CE and its relevance to the business firms through production, use and end-of-life management strategies for their products. It illustrates the different elements of a circular economy, and where in the life cycle these should be addressed.

The theory from IE contributes to CE in different ways. According to Saavedra et al. (2018), this contribution can be structured along three levels:

1. Conceptual contribution
2. Technical contribution
3. Political and standard contribution

The conceptual contribution is related to category 4 in Table 11.1 where CE aligns with industrial symbioses (IS), which involves the exchange of by-products and wastes in planned complexes of co-located manufacturing plants thereby increasing the intensity of resource use by adding value from the same initial inputs. The technical contribution concerns the use of IE tools as presented in the CapSEM Model to support CE. According to Saavedra et al. (2018), the most commonly used tools are MFA, Design for the Environment (DfE) and Cleaner Production (CP).

However, CE can be linked to all Levels presented in the CapSEM Model (see Table 2.1 in Chap. 2, Part I of this book). If a product is designed favouring recycling combined with economic incentives, the potential to close material loops is high. The political and standard contribution is manifested in the application of IE to support the development of policies, laws, and standards to implement CE. To achieve this systematic transition towards a CE at a macro level, the collaboration of the business community, policymakers and institutions is fundamental, as intented by SDG number 17, 'Partnership'. Some policy instruments can be applied in this broader context of CE, such as regulatory instruments, research and educational instruments, technology transfer and informational instruments (e.g., eco-labelling).

There are numerous models for the circular economy. The circular economy system diagram, known as the butterfly diagram, see Fig. 11.3, is often employed (MacArthur 2013). Two principle cycles, technical and biological are used to demonstrate the continuous flow of materials in the economy. In the first, the way in which products are retained in circulation in the economy is by reusing, repairing, remanufacturing and recycling them. Materials are thus constantly used and never become waste. In the second, nutrients from biodegradable materials are returned to the Earth, through composting or anaerobic digestion. This permits the land to regenerate. The cycle then continues (MacArthur 2013).

Although there have been several attempts to define the scope of CE, critics claim that it is interpreted differently by different people. Kirchherr et al. (2017)

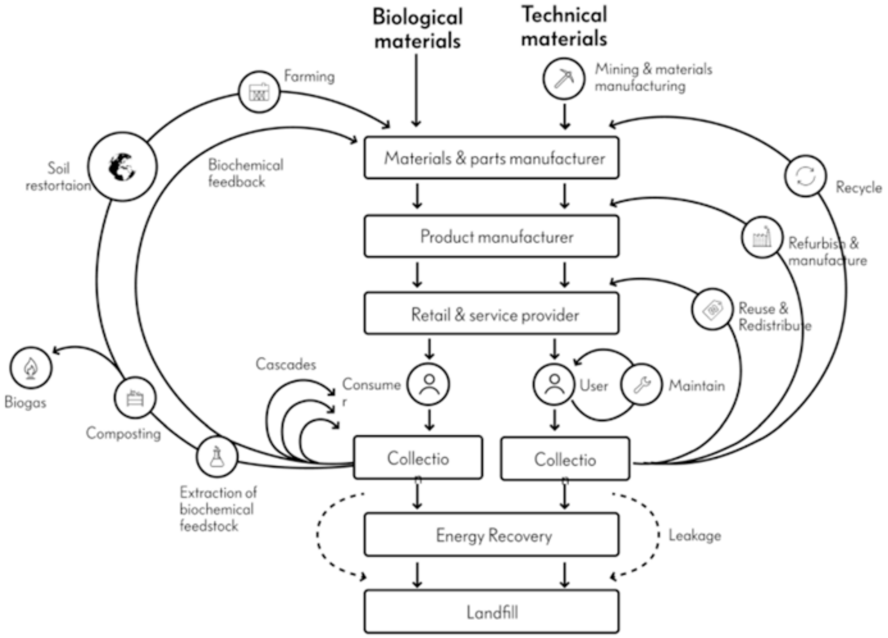

Fig. 11.3 The butterfly diagram: visualising the circular economy (ellenmacarthurfoundation.org, 2013)

report that more than 100 different definitions of circular economy are found in scientific literature. The definitions are often linked to the author's discipline which can render them confusing for researchers outside the discipline. According to Murray et al. (2017), the uses of the words *circular* and *linear*, in association with the word *economy* are potentially confusing as both links exist in entirely different contexts. While CE has been linked closely to IE and the environmental dimension of sustainability in this chapter, reflections on the social dimension have been less visible. So, for the implementation of CE in business, the social value should also be visible to avoid oversimplification of the concept. Considering these issues, Murray et al. (2017) have suggested the following definition:

> The Circular Economy is an economic model wherein planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximize ecosystem functioning and human well-being.

11.4 Material Flow Analysis

Material Flow Analysis (MFA) studies the physical flows of natural resources and materials into, through and out of a given system. It is based on methodically organised accounts in physical units. It uses the principle of mass balancing to analyze the relationships between material flows (including energy), human activities (including economic and trade developments) and environmental changes (OECD 2008). The basic principle of MFA simply applies the law of conservation of energy and mass: *matter is neither created nor destroyed*. MFA exemplifies what this law means in practice and how practitioners can demonstrate the law of conservation in solving real-life problems with varying degrees of complexity related to environmental management. The roots of MFA also lie in the material balance calculations in chemical engineering problems. Material balance is simply accounting for material, and it is often compared to the balancing of financial accounts. Money is deposited and withdrawn. The difference between these transactions at the end of the fixed time is accumulation in the account, also called the *Stock* in MFA terminologies. Because of the law of conservation of matter, the results of an MFA can be controlled by a simple material balance comparing all inputs, stocks, and outputs of a process. This distinct characteristic of MFA makes the method attractive as a decision-support tool in resource management, waste management, and environmental management (Brunner and Rechberger 2016).

11.4.1 MFA Methodology

MFA can be used for assessing various systems or scenarios. The terms *material* or *substance flow analysis* (MFA or SFA) are used interchangeably in the literature depending on the study unit, material or substance. MFA can be classified either by material type, analytical scope, chemical ingredient, or research purpose, providing

Table 11.2 Essential terminology in MFA studies

Term	Definition
Material	Material stands for both substances and goods
Substance	In chemistry, a substance is defined as a single type of matter consisting of uniform units.
Goods	Goods are substances or mixtures of substances that have economic values assigned by markets.
Process	A process is defined as the transport, transformation, or storage of materials.
Stock	Stocks are defined as material reservoirs (mass) within the analyzed system, and they have the physical unit of kilograms. A stock is part of a process comprising the mass that is stored within the process.
Flow and flux	Processes are linked by flows (mass per time) or fluxes (mass per time and cross-section) of materials. Flows/fluxes across systems boundaries are called imports or exports. Flows/fluxes of materials entering a process are named inputs, while those exiting is called outputs
System	A system comprises a set of material flows, stocks, and processes within a defined boundary
System boundary	The system boundary is defined in space and time. It can consist of geographical borders (region) or virtual limits (e.g., private households, including processes serving the private household such as transportation, waste collection, and sewer system)
Substance flow analysis (SFA)	Substance flow analysis (SFA) monitor flows of specific substances (e.g. Cd, Pb, Zn, Hg, N, P, CO2, CFC) that are known for raising particular concerns as regards the environmental and health risks associated with their production and consumption (OECD 2008).
Material system analysis (MSA)	Material system analysis (MSA) is based on material-specific flow accounts. It focuses on selected raw materials or semi-finished goods at various Levels of detail and application (e.g., cement, paper, iron and steel, copper, plastics, timber, water) and considers life-cycle-wide inputs and outputs. It applies to materials that raise particular concerns as to the sustainability of their use, the security of their supply to the economy, and/or the environmental consequences of their production and consumption. (OECD 2008)

Modified from Brunner and Rechberger (2016)

the potential to assess sustainability from various analytical perspectives. Before exploring the methodological steps, it is essential to understand the terminology used in describing the MFA study. Table 11.2 provides a brief overview of all the critical terms for an MFA study.

Figure 11.4 demonstrates the typical system flow diagram for MFA for a system. P1 and P2 are processes, and S1 is the stock within P1 where the material is accumulated. Here, $A_{0,1}$, $A_{1,2}$, $A_{2,1}$ and $A_{2,0}$ are the flows from which material and substance enter the system. As per the definition of a process, the material is either transformed, transferred or stored in the process represented by boxes.

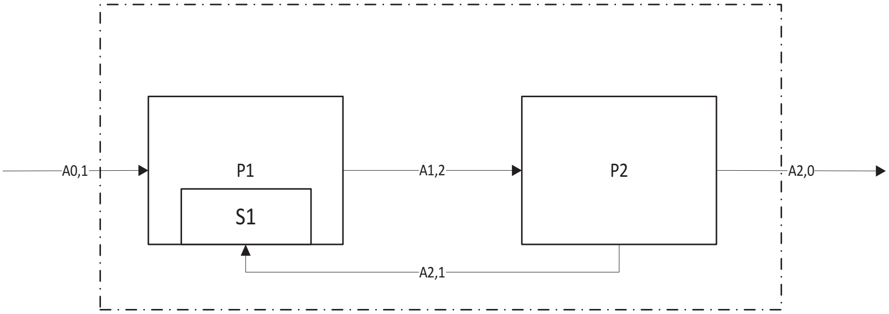

Fig. 11.4 Typical process flow diagram for the MFA system

According to the law of conservation of matter, the mass balance equations for each process can be represented as follows:

$$\sum Input\ flows = \sum Output\ flows + \sum Stocks$$

$$Change\ in\ Stock \frac{\Delta S1}{\Delta t} = A_{0,1} + A_{2,1} - A_{1,2}$$

$$Mass\ balance\ for\ Process\ P2 : A_{1,2} - A_{2,1} - A_{2,0} = 0$$

If inputs and outputs do not balance when mapping the MFA system, then one or several flows are either missing or have been wrongly calculated. The mass-balance principle applies to systems, sub-systems and processes. An accurate material balance of a system or a process is only achieved if all input and output flows are known or measured. In practice, stocks are often calculated by the difference between inputs and outputs. All the necessary information for calculating material flows should be available from a variety of sources such as company records, national reports, statistical databases, and published scientific literature. In some instances, relevant stakeholders and resource users can be targeted to gain insights into the system to be studied (Deshpande et al. 2020). After calculating all the flows, the mass balance of the system needs to be checked, and uncertainties of the obtained information need to be evaluated. MFA studies involving several flows, processes and stocks tend to become complicated. Dividing processes into sub-processes, re-adjusting system boundaries or using analytical software for calculations are the few techniques to approach the complicated MFA systems. Brunner and Rechberger (2016) describe calculations protocols, uncertainty analysis, and various software packages available for conducting MFA in their ‘Practical Handbook of Material Flow Analysis’.

Table 11.3 Type and application of MFA, based on objectives of interest

Specific environmental problems related to certain impacts per unit flow of:		
Ia	**Ib**	**Ic**
Substance	*Materials*	*Products*
e.g., Cd, Cl, Pb, Zn, Hg, N, P, C, CO_2, CFC	e.g., wooden products, energy carriers, excavation, biomass, plastics	e.g., diapers, batteries cars
Problems of environmental concern related to the throughput of:		
IIa	**IIb**	**IIc**
Firms/industry	*Sector*	*Region*
e.g., single plants, medium and large companies	e.g., production sectors, chemical industry, construction	e.g., total or main throughput mass flow balance, total material requirement

11.4.2 MFA Applications

An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. The depletion or accumulation of material stocks is identified early enough to take countermeasures or promote further build-up and future utilization. Moreover, minor changes that are too small to be measured in short time scales but could slowly lead to long-term damage also become evident. Historically, MFA is applied through various scales from a global or national level to a company, product, and process level. In general, MFA provides a system-analytical view of various interlinked processes and flows to support the strategic and priority-oriented design of management measures. Table 11.3 presents the overview of MFA connecting to the application at various levels, i.e., substance (Ia), materials (Ib), and products (Ic) (Bringezu et al. 1997). These refer to Levels 1 and 2 in the CapSEM Model. The CapSEM model suggests that MFA at Level 1 is accounted for by each production process's inputs and outputs (I/O). The accounting embraces both substances and other materials, as shown in Table 11.3. Similarly, for products viewed in a life cycle perspective. This is noted under Ic in the table. Levels 3 and 4 in the CapSEM model are represented by firms (IIa), sectors (IIb), and regions (IIc) in Table 11.3. The firm-level MFAs help realize sustainability goals by uncovering major problems existing in the production phase and across the product life cycle, supporting priority setting, checking the possibilities for improvement measures, and providing tools for monitoring their effectiveness.

The environmental performance indicators (EPIs) assessed through MFA studies, complement the sustainability reporting and other tools used to assess the firm's environmental performance management through tools such as input-output analyses and life cycle assessment (LCA). The insights gained through applying MFAs within industries helps in designing corporate strategies for regulatory compliance, resource conservation, and waste management, waste prevention or circular economy.

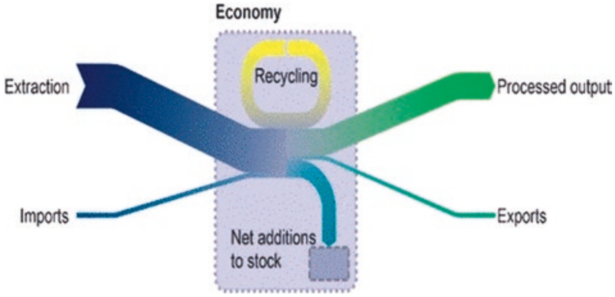

Fig. 11.5 Representative illustration of MFA through Sankey diagram (Schmidt 2008a, b)

Historically, MFA has been used for a wide range and scale of applications. Binder (2007) classifies the applications of MFA between industrial and regional scale analysis. MFA results have successfully been used to optimize material flows and waste streams in production. MFA is a central methodology used within industrial ecology and quantifies how the materials that enable modern society are used, reused and lost (Bringezu S and Moriguchi Y 2002). Sankey diagrams named the ‘visible language of industrial ecology’, are often employed to present MFA results, see Fig. 11.5. Such a model exemplifies a mass balance between extracting natural resources and importing goods or resources, with outputs represented as exported goods, and other processed outputs. Differences between inputs and outputs become additions to national reserves. Recycling guarantees the retention of these elements within the national economy which is consistent with the definition of a circular economy.

Moreover, industrial eco-parks are based on optimizing material flows within different industry sectors, which can be assessed using MFA (Chertow 2000). On a regional scale, MFA results could be applied to derive measures for improving regional, or corporate, management of materials: to optimize resource exploitation, consumption, and environmental protection within the particular constraints of the region or company (Binder 2007).

11.5 Conclusion

MFA approaches are now being linked with environmental input-output assessment, life cycle assessment and scenario development. These increasingly comprehensive assessments promise to be central tools for future sustainable development and circular economy studies (Graedal 2019). Industrial Metabolism (IM) and Industrial Symbioses (IS) are also more often referred to in studies of applied IE (Oughton et al. 2022). This chapter has assessed the history and status of MFA, reviewed the development of the methodology, and demonstrated that MFAs have been responsible for creating related industrial ecology specialities and stimulating connections between industrial ecology and a variety of engineering and social science fields. Closing the loop for the preservation of scarce planetary resources requires the collaborative efforts of participants at all levels of society. An idealized end-state has been loosely described as a circular economy. The CapSEM Model offers both a transition pathway and specific methods to achieve this objective.

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