Chapter 3
Industrial Ecology and Input-Output Economics: A Brief History

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Introduction

It has been only a few hundred years since human society escaped from a constant cycle of ebb and flow of population changes. Famines and epidemics were mingled with preindustrial European and Asian history, repeatedly setting the human population of the region several decades to hundreds years back (Braudel 1979). It was industrialization, together with the green revolution, that enabled humans to manipulate the untamed nature, setting the humankind free from the famines and epidemics that kept its population at a much lower level throughout its history. The burst of human population in recent centuries, however, is not only a consequence of industrialization but in a sense also a cause of industrialization. Fulfilling the needs by the unprecedented number of people required intensification and efficiency in industrial and agricultural production, which in turn helped generate more economic surplus enabling consuming even more. The human kind seemed to have won an autonomy, of which the prosperity somehow self-catalyzes and works independently from the means that the nature provides.

Ironically, however, humans became more dependent upon the natural environment both as a source of natural resources and as a sink of wastes and pollution. Despite the remarkable technological developments, population growth and improvements in welfare demanded an unprecedented amount of natural resources withdrawal from and wastes and pollutants disposal to the nature. Global crude oil extraction, iron ore mining, and underground water withdrawal, to name a few, are at their highest to satisfy the needs of the ever wealthier and populous human-kind.

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Around 26 billion barrels of crude oil are extracted every year (EIA 2008), enough to fill over five Olympic-size stadiums every day (Suh 2004a). Per capita copper use until 1900 is estimated to be below 1 kg/year, which has become around 15 kg/year by 2000 (Gordon et al. 2006). The U.S. total materials use is estimated to be less 200 million metric tons at the dawn of the twentieth century, and it reached nearly 3,000 million metric tons by 1995 (Gardner and Sampat 1998).

All the non-renewable resources extracted from the environment are processed, transformed, used, and discarded; but after being discarded they persist somewhere in the nature or in the built environment in a variety of different physical forms. As a general pattern, stable chemicals, which had been safely isolated under the Earth's crust in the form of ores, crude oil and natural gas, are now present instead in more active and available forms. Many of the pollutants that are considered to be the causes of modern environmental problems, such as CO_2, heavy metals and other toxic substances, were extracted from the environment or synthesized thereof at an earlier stage of their life cycles. Thus, the extraction of natural resources for economic use is closely connected with the environmental problems by the intricate channels by which the modern economy transforms, uses and disposes of the inputs and outputs of the production system. Therefore, understanding the structure of the economy that governs material and energy flows between producing industries and consuming households is indispensable for solving the problems of both limited availability of natural resources and pollution.

Recognizing the inherent linkage between natural resource use and pollutant emissions, industrial ecology takes a systems approach that addresses the problems at both ends of the production chain. Industrial ecology aims at closing material cycles within the industrial system by developing symbiotic relationships among industries (Frosch and Gallopoulos 1989; Graedel and Allenby 1995; Ayres and Ayres 1996; Graedel 2002a).[1] In industrial ecology, an industrial system is viewed as a complex organism that processes energy and materials under its own metabolic rules (see, e.g., Kneese et al. 1970). How industrial systems are structured and how they transform, use and discard natural resources is therefore the major focus of industrial ecology.

Input-output economics describes and analyzes the structure of an economy in terms of the interactions among industries and between them and households. Thus, the relevance of input-output economics for industrial ecology seems evident. While this overlap of concerns was already recognized in the early years of the young field of industrial ecology (Duchin 1990, 1992; Lave et al. 1995), and some progress has certainly been made in exploiting it, widespread communication and effective collaboration between the two disciplines are still at an early stage.

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[1] A discussion of the definition and goals of industrial ecology is provided by (Lifset and Graedel 2002).

History of Input-Output Analysis in Industrial Ecology

Industrial Ecology

As described in the previous section, industrial ecology seeks to close material cycles by developing symbiotic relationships among industries. One application of this concept is the so-called Eco-Industrial Park (EIP), such as Kalundborg in Denmark, where an industrial complex was evolved or designed to maximize the use of internal outputs and wastes from one establishment in another and to minimize the resource inputs and wastes associated with the entire complex (Ehrenfield and Gertler 1997; Chertow 1998). To our knowledge, such an idea was first articulated in the English-speaking world by Barry Commoner (Commoner 1971). In his book, *The Closing Circle*, Commoner simply but accurately described the origin of environmental problems as the lack of closing circles in the exchange of materials between society and the environment. If the ‘circles’ of material utilization indeed could be closed within the industrial systems by efficiently managing materials, environmental problems associated with virgin material inputs and waste outputs could be more systematically handled. His idea was not, however, widely hailed by the scientific community at that time. Besides Commoner’s admonitions, several studies conducted in Belgium and Japan in the 1970s were concerned with the same issue, and they even used a term that would be translated as ‘industrial ecology’ in English (Erkman 1997).

It was clearly Frosch and Gallopoulos (1989), however, who coined the term ‘industrial ecosystem’ and drew broader international attention to the concept, providing critical momentum for developing industrial ecology as a distinct scientific field. Under the leadership of these authors, the National Academy of Engineering of the United States played an important role in hosting and further building industrial ecology discourses. Since then the field has not only diversified but also deepened in many respects embracing, e.g., Life Cycle Assessment (LCA), Material Flow Analysis (MFA), EIP development, sustainable production and consumption, earth systems engineering, policy analysis, etc. (Graedel and Allenby 1995; Ayres and Ayres 1996; Ehrenfield and Gertler 1997; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998; Allenby 1999a; Matthews et al. 2000; van der Voet et al. 2000; Graedel 2002a; Graedel 2002b; Hertwich 2005). To better facilitate communication within the growing industrial ecology community, the *Journal of Industrial Ecology* was launched in 1997. The first Gordon Research Conference in Industrial Ecology was held in 1998 and now takes place on a biennial basis. The International Society of Industrial Ecology (ISIE) was created in 2001, with its first biannual international conference held in Leiden in the same year.

Input-Output Analysis in Industrial Ecology: Historical Roots and its Propagation

Although it was the pioneering contributions by Duchin (1990, 1992) that explicitly made the link between input-output economics and industrial ecology, developments in input-output economics had previously touched upon the core concept of industrial ecology. Wassily Leontief himself incorporated key ideas of industrial ecology into an input-output framework. Leontief (1970) and Leontief and Ford (1972) proposed a model where the generation and the abatement of pollution are explicitly dealt with within an extended IO framework. This model, which combines both physical and monetary units in a single coefficient matrix, shows how pollutants generated by industries are treated by so-called 'pollution abatement sectors.' Although the model has been a subject of long-standing methodological discussions (Flick 1974; Leontief 1974; Lee 1982), its structure captures the essence of industrial ecology concerns: abatement of environmental problems by exploiting inter-industry interactions. As a general framework, we believe that the model by Leontief (1970) and Leontief and Ford (1972) deserves credit as an archetype of the various models that have become widely referred to in the field of industrial ecology during the last decade, including mixed-unit IO, waste IO and hybrid Life Cycle Assessment (LCA) models (Duchin 1990; Konijn et al. 1997; Joshi 1999; Nakamura and Kondo 2002; Kondo and Nakamura 2004; Kagawa et al. 2004; Suh 2004b). Notably, Duchin (1990) deals with the conversion of wastes to useful products, which is precisely the aim of industrial ecology, and subsequently, as part of a study funded by the first AT&T industrial ecology fellowship program, with the recovery of plastic wastes in particular (Duchin and Lange 1998). Duchin (1992) clarifies the quantity–price relationships in an input-output model (a theme to which she has repeatedly returned) and draws its implications for industrial ecology, which has traditionally been concerned exclusively with physical quantities.

Duchin and Lange evaluated the feasibility of the recommendations of the Brundtland Report for achieving sustainable development. For that, Duchin and Lange (1994) developed an input-output model of the global economy with multiple regions and analyzed the consequences of the Brundtland assumptions about economic development and technological change for future material use and waste generation. Despite substantial improvements in material efficiency and pollution reduction, they found that these could not offset the impact of population growth and the improved standards of living endorsed by the authors of the Brundtland Report.

Another pioneering study that greatly influenced current industrial ecology research was described by Ayres and Kneese (1969) and Kneese et al. (1970), who applied the mass-balance principle to the basic input-output structure, enabling a quantitative analysis of resource use and material flows of an economic system. The contribution by Ayres and Kneese is considered as the first attempt to describe the metabolic structure of an economy in terms of mass flows (see Ayres 1989; Haberl 2001).

Since the 1990s, new work in the areas of economy-wide research about material flows, sometimes based on Physical Input-Output Tables (PIOTs), has propelled this line of research forward in at least four distinct directions: (1) systems conceptualization (Duchin 1992, 2009), (2) development of methodology (Konijn et al. 1997; Nakamura and Kondo 2002; Hoekstra 2003; Suh 2004c; Giljum and Hubacek 2004; Dietzenbacher 2005; Dietzenbacher et al. 2009; Weisz and Duchin 2005), (3) compilation of data (Kratterl and Kratena 1990; Kratena et al. 1992; Pedersen 1999; Ariyoshi and Moriguchi 2003; Bringezu et al. 2003; Stahmer et al. 2003), and (4) applications (Duchin 1990; Duchin and Lange 1994; Duchin and Lange, 1998; Hubacek and Giljum 2003; Kagawa et al. 2004). PIOTs generally use a single unit of mass to describe physical flows among industrial sectors of a national economy. In principle, such PIOTs are capable of satisfying both column-wise and row-wise mass balances, providing a basis for locating materials within a national economy.[2] A notable variation in this tradition, although it had long been used in input-output economic studies starting with the work of Leontief, is the mixed-unit IO table. Konijn et al. (1997) analyzed a number of metal flows in the Netherlands using a mixed-unit IO table, and Hoekstra (2003) further improved both the accounting framework and data. Unlike the original PIOTs, mixed-unit IOTs do not assure the existence of column-wise mass-balance, but they make it possible to address more complex questions. Lennox Turner, Hoffman, and McInnis (2004) present the Australian Stocks and Flows Framework (ASFF), where a dynamic IO model is implemented on the basis of a hybrid input-output table. These studies constitute an important pillar of industrial ecology that is generally referred to as Material Flow Analysis (MFA).[3]

Although the emphasis in industrial ecology has arguably been more on the materials side, energy issues are without doubt also among its major concerns. In this regard, energy input-output analysis must be considered another important pillar for the conceptual basis of ‘industrial energy metabolism.’ The oil shock in the 1970s stimulated extensive research on the structure of energy use, and various studies quantifying the energy associated with individual products were carried out (Berry and Fels 1973; Chapman 1974). Wright (1974) utilized Input-Output Analysis (IOA) for energy analysis, which previously had been dominated by process-based analysis (see also Hannon 1974; Bullard and Herendeen 1975; Bullard et al. 1978). The two schools of energy analysis, namely process analysis and IO energy analysis, were merged by Bullard and Pilati (1976) into hybrid energy analysis (see also van Engelenburg et al. 1994; Wilting 1996). Another notable contribution to the area of energy analysis was made by Cleveland et al. (1984), who present a comprehensive analysis, using the US input-output tables, quantifying the interconnection of energy and economic activities from a biophysical standpoint (see

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[2] Recent discussions have focused on the treatment of ‘disposal to nature’ in a PIOT. Interested readers are encouraged to consult Hubacek and Giljum (2003), Suh (2004c), Giljum and Hubacek (2004), Dietzenbacher (2005), Dietzenbacher et al. (2009), Weisz and Duchin (2006).

[3] The same acronym is sometimes used in the input-output domain to refer to Minimal Flow Analysis (see, e.g., Schnabl 1994 1995). In this text MFA means only Material Flow Analysis.

Cleveland 1999; Haberl 2001; Kagawa and Inamura 2004). These studies shed light on how an economy is structured by means of energy flows and informs certain approaches to studying climate change (see, e.g., Proops et al. 1993; Wier et al. 2001).

What generally escapes attention in both input-output economics and industrial ecology, despite its relevance for both, is the field of Ecological Network Analysis (ENA). Since Lotka (1925) and Lindeman (1942), material flows and energy flows have been among the central issues in ecology. It was Hannon (1973) who first introduced concepts from input-output economics to analyze the structure of energy utilization in an ecosystem. Using an input-output framework, the complex interactions between trophic levels or ecosystem compartments can be modeled, taking all direct and indirect relationships between components into account. Hannon's approach was adopted, modified and re-introduced by various ecologists. Finn (1976,1977), among others, developed a set of analytical measures to characterize the structure of an ecosystem using a rather extensive reformulation of the approach proposed by Hannon (1973). Another important development in the tradition of ENA is so-called environ analysis. Patten (1982) proposed the term "environ" to refer to the relative interdependency between ecosystem components in terms of nutrient or energy flows. Results of environ analysis are generally presented as a comprehensive network flow diagram, which shows the relative magnitudes of material or energy flows between the ecosystem components through direct and indirect relationships (Levine 1980; Patten 1982). Ulanowicz and colleagues have broadened the scope of materials and energy flow analysis both conceptually and empirically (Szyrmer and Ulanowicz 1987). Recently Bailey et al. (2004a, b) made use of the ENA tradition to analyze the flows of several metals through the US economy. Suh (2005) discusses the relationship between ENA and IOA and shows that Patten's environ analysis is similar to Structural Path Analysis (SPA), and that the ENA framework tends to converge toward the Ghoshian framework rather than the Leontief framework although using a different formalism (Defourny and Thorbecke 1984; Ghosh 1958).

Recent Progress

Recent developments have situated LCA, a key subfield of industrial ecology, as one of the areas that most extensively utilize IOA.[4] LCA is a tool for quantifying and evaluating the environmental impacts of a product over the course of its entire life-cycle (ISO 1998; Guinée et al. 2002). Similar to the energy analyses in the 1970s, LCAs have been generally based on so-called process-analysis, where information identifying and quantifying inputs and outputs of a product system is collected at the detailed unit-process level. As collecting process-level data is time-consuming

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[4] In this chapter we use the term input-output analysis, or IOA, to denote concepts and methods first developed by input-output economists but now used extensively also by practitioners who are not economists.

and costly, it has been the general practice in conducting LCA to focus only on a selected set of processes causing so-called truncation errors (Lave et al. 1995; Lenzen 2000). Addressing the problem of truncation, Moriguchi et al. (1993) applied both IOA and process analysis in calculating the life-cycle CO_2 emissions of automobiles in Japan, forming a hybrid LCA approach. Nevertheless it was the series of studies at Carnegie Mellon University that provided a critical impetus in this direction of research under the banner of "Environmental Input-Output Life Cycle Assessment" or EIO-LCA (Lave et al. 1995; Flores 1996; Horvath and Hendrickson 1998; Hendrickson 1998; Joshi 1999; Hendrickson and Horvath 2000; Rosenblum et al. 2000; Matthews and Small 2001).[5] Lave et al. (1995) utilized the rich environmental statistics of the US and constructed a comprehensive environmental IO database for use in LCA. The tradition of input-output LCA in Carnegie Mellon University has been diversified addressing various issues, notably building materials and infrastructure (see, e.g., Horvath and Hendrickson 1998; Horvath 2004),[6] information infrastructure (Matthews et al. 2002), hybrid LCA (Joshi 1999; Matthews and Small 2001) and heavy metal flows in the US. Currently IOA is an important part of LCA practice and both methods and data for IO- and hybrid LCA are under rapid development (see Norris 2002; Lenzen 2002; Suh and Huppes 2002, 2005; Lenzen et al. 2004; Suh 2004b; Suh et al. 2004).[7]

The recent contributions of Faye Duchin and her colleagues situate studies based on both input-output economics and industrial ecology in a global framework. The World Trade Model developed by Duchin (2005) is a linear program that solves for both physical flows and associated prices on the basis of comparing physical stocks and technologies, and the associated cost structures, in all potential trade partners. The model has been used to examine the global implications of the changes in agricultural land yields due to future climate change (Juliá and Duchin 2005) and to evaluate the global trade-offs between cost-reduction and reduction in carbon emissions (Strømman et al. 2005).

Another area where IOA is widely used in conjunction with industrial ecology is the product policy field. The value of Integrated Product Policy (IPP) became widely acknowledged within European policy frameworks, notably the sixth Environmental Action Programme (EC 2001a). The product-oriented life-cycle approach taken by IPP was regarded as an important innovation in Environmental policy directives. In 2003, the European Commission adopted a Communication (EC 2003) that identifies products with the greatest potential for environmental improvement as a basis for implementing IPP. This involves quantifying environmental impacts of various products in an economy and investigating further the identified target products.

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[5] The heavily accessed web-based database of <www.eiolca.net> provide online LCA database based on 1992 and 1997 US benchmark IOTs.

[6] Acknowledging his achievements toward industrial ecology, including his contributions to EIO-LCA and industrial ecology of infrastructure, the ISIE awarded the second Laudise prize to Arpad Horvath in 2005.

[7] The International Journal of Life Cycle Assessment, which is the only international journal devoted entirely to the development of LCA, launched a section on IO- and hybrid LCA in 2004.

Naturally, IO-LCA has been recognized as one of the approaches well suited to IPP analyses. Weidema et al. (2004), for instance, compiled an international IO table with environmental extensions and utilized it for prioritizing environmentally important products in Denmark. Tukker et al. (2005) analyzed environmentally important products in EU25 using an environmentally extended input-output table where consumption is endogenous.[8]

IOA is rapidly broadening its scope of application in industrial ecology on other fronts as well. Ukidwe and Bakshi (2004) applied the second law of thermodynamics, or the entropy law, for the US economy using an input-output framework to analyze degradation of energy quality along the production chain of a product (see also Ukidwe et al. 2009). Many input-output tables are now supplemented with data on natural resource use and environmental emissions at an industry level of detail. Notable progress in this line of development includes the increasing number of natural resource accounts such as water accounts, land accounts and forestry accounts (see, e.g., Vincent 1997; Hellsten et al. 1999; Hubacek and Giljum 2003; Lange et al. 2003), which parallel the corresponding evolution in accounting systems such as Systems of Environmental and Economic Accounts (SEEA) and National Accounting Matrices including Environmental Accounts (NAMEA) (see, e.g., de Haan and Keuning 1996; EC 2001b; UN 2003).

Future of Input-Output Economics in Industrial Ecology

There are notable commonalities of intellectual grounds shared by Input-Output Economics and Industrial Ecology. In introducing Earth Systems Engineering and Management (ESEM), Braden Allenby advanced the idea that the world has become an artifact, by which he means that increasingly numerous aspects of the world have become part of engineered systems that are managed by humans (Allenby 1999b, 2000; see also Keith 2000). Whether such a change is desirable or not is debatable, the direction of change seems difficult to refute: as human influence over the physical, chemical and biological metabolism of the earth system becomes increasingly dominant, our $56 trillion economy needs a managerial ethos that matches the magnitude of the challenges, and industrial ecology undertakes to provide one. By contrast with other approaches to economics, which emphasize market competition based on self-interested, “rational” behavior on the parts of individual agents, input-output economics lends itself more readily to the analysis of alternative approaches to managerial and policy decision-making.[9]

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[8] Similar projects are currently being undertaken in Sweden (Wadeskog A. 2005, Personal communication).

[9] Karen Polenske has pointed out that compilation of input-output tables has been criticized in the US on the grounds that input-output analysis was a communistic idea, while it has been criticized in China on the grounds of its capitalistic orientation.

The strong emphasis on a systems view is another commonality between the two fields. One of Wassily Leontief's motivations in developing input-output theory was the recognition of the limitations of "partial" analysis. In his autobiography for the Nobel Foundation he noted: "[P]artial analysis cannot provide a sufficiently broad basis for fundamental understanding." The message, which points out that an analysis based on only part of a system may be misleading if it neglects strong interactions with the embedding system, is precisely the one industrial ecology endorses.

Both input-output economics and industrial ecology place strong emphasis on real-world data. Many of the research efforts in industrial ecology are devoted to developing sound empirical knowledge on how materials flow and accumulate around the globe (Lave et al. 1995; Matthews et al. 2000; Graedel 2002b; Nansai et al. 2003; Graedel et al. 2004; Suh 2004d). The importance of empirical grounding for an economic model has nowhere been stressed more than in input-output economics since its inception. In one of his speeches to the materials science community, Leontief stated (Leontief 1975):

> A model is essentially a theoretical construct which enables us, starting with some actual or hypothetical data, to arrive at some interesting empirical conclusions. It must start on the ground. It must end on the ground. In between, you can fly as high as you want, but land on the ground again. There are too many models which are still flying.

Given these common intellectual grounds between the two disciplines, what are the roles played by input-output economics in the field of industrial ecology? We choose to reflect on the main patterns of how IOA has been, and is being, utilized in the context of industrial ecology.

Most importantly, IOA has always had the ambition to facilitate interdisciplinary research by connecting different disciplines. Despite its conceptual and operational simplicity, the input-output framework encompasses price and quantity relationships, production factors and technology, income distribution, labor and capital investments, international trade, dynamics and structural change. This vast scope opens up the possibilities of integrating different fields of science using the input-output framework as a common medium. As it deals with problems at a systems level, many questions that industrial ecology poses demand close cooperation of engineers and natural scientists with economists and other social scientists. Input-output economics can provide a platform for industrial ecology where actors from different disciplines share a common ground and use it as a gateway to increasingly ambitious research agendas. Furthermore, as an efficient accounting structure, the formalisms for compiling input-output data are used, though sometimes in modified forms, in various applications including ENA, LCA and MFA, enabling common understandings and a ground for integration.

As compared to industrial ecology, input-output economics is a mature scientific field. Given the overlapping and adjoining areas of interests of the two disciplines, the rich understanding of productive systems accumulated over the long history of input-output economics can be a valuable knowledge base for approaching various issues in industrial ecology.[10] For instance, the discussions about allocation in LCA during the past 15 years mirror discussions that have taken place among input-output economists since the early 1960s under the banner of the "make" and "use" framework (Stone et al. 1963; Konijn 1994; Heijungs and Suh 2002; Kagawa and Suh 2009). The diverse analytical tools and models developed by input-output economists, which include but are not limited to structural path analysis, key sector analysis, structural decomposition analysis, and minimal flow analysis as well as dynamic input-output models, optimal choice-of-technology models, and models of the world economy, have direct relevance for conceptual representation and analysis of applied questions in industrial ecology as well (see, e.g., Treloar 1997; Lenzen 2002, 2003; Heijungs and Suh 2002; Hoekstra, 2003; Suh 2004b; Duchin 2009).

From a practical perspective, the input-output table provides valuable statistical information for industrial ecologists. The input-output table is one of the only publicly available statistics based on a well-established method of compilation that reveals the structure of inter-industry interdependence at a national level. One of the major difficulties in pursuing research in industrial ecology, as in many other disciplines, is the difficulty of obtaining reliable data from industry and the cost of collecting such data. In that regard, an input-output table is an important data source for industrial ecologists: hybrid LCA, for instance, utilizes an input-output table to describe the inter-industry exchanges of the background system that is connected to a more detailed engineering model describing inter-process exchanges (Joshi 1999; Suh 2004b; Suh and Huppes (2005).

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[10] In her Presidential Address to the 15th International Input-Output Conference, Duchin (2005) presented a vision about collaboration between input-output economists and industrial ecologists. She stressed resources as the main area of overlap and common interests and attempted to remove some remaining conceptual obstacles to more intensive and fruitful collaboration.

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