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An Economic Perspective on Industrial Ecology¹

Edward J. Manderson² and Timothy J. Considine³

Abstract: Industrial ecology aims to identify how the environmental performance of industrial systems can be improved. Key analytical tools of industrial ecology include material flow analysis, which tracks flows of materials from source to sink, and life cycle assessment, which quantifies the environmental impacts of a product across all stages of its life cycle. Although industrial ecology is considered to be a multidisciplinary field that includes the social sciences, economic analysis has not been fully incorporated into the industrial ecology literature and vice versa. Thus, both industrial ecology and economics would likely benefit from closer collaboration. The main objectives of this article are: (1) to introduce key concepts and techniques of analysis in industrial ecology; (2) to identify important developments at the intersection of industrial ecology and economics; and (3) to suggest areas for future collaboration and integration of the two disciplines. We argue that economists can play an important role in expanding and deepening industrial ecology and addressing the current gaps in the literature, thus improving the ability of industrial ecology to reach its full potential as a policy-supporting tool.

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INTRODUCTION

Industrial ecology is a field of study that systematically examines material and energy uses and flows in industrial systems, in order to identify how the environmental performance of industry can be improved. Although industrial ecology began to emerge as a research field in the early 1990s,⁴ its intellectual foundations were established much earlier. In a particularly influential paper, Ayres and Kneese (1969) explained that all consumption and production activities involve the transformation of materials and the dissipation of energy, and thus generate pollution to some degree. This means that environmental externalities are an inevitable part of economic processes. With the ubiquitous nature of these externalities in mind, Ayres and Kneese (1969) developed a formal mathematical framework for tracing environmental residuals throughout the economy.

Ayres and Kneese (1969) inspired further research in this area (Kneese et al. 1970; Noll and Trojonis, 1971; Converse, 1971; Russell, 1973), and in 1989, the authors received the publication of enduring quality award from the Association of Environmental and Resource Economists. They based their analysis on the material (or mass) balance principle, which states that materials can neither be created nor destroyed in an economic process; only their form can be changed.⁵ Ayres and Kneese (1969) continued to attract attention as researchers applied the material balance approach to systematically examine the flow of materials and energy through society, in

⁴ For information on the history of industrial ecology, see Erkman (2002).

⁵ The material balance principle is a simple application of the law of conservation of mass – i.e., that the mass of a closed system must remain constant over time.

order to understand the causes of pollution from a holistic perspective. Ayres (1994) refined this approach by introducing the concept of industrial metabolism, which refers to the collection of physical processes that convert raw materials, energy, and labor into economic output and wastes.

Like industrial metabolism, the industrial ecology paradigm involves the examination of material and energy flows from a systems perspective. However, industrial ecology goes further by considering how firms can move toward a *closed loop system*, where waste streams are recovered, recycled, and reused as inputs for new production processes. Lifset and Graedel (2002) describe industrial ecology as being “ecological” in at least two ways. First, industrial ecology emphasizes the importance of the biophysical environment to economic activity in supplying inputs of raw materials and fuels and in providing a waste sink for pollutants from consumption or production. This raises the issues of carrying capacity and ecological resilience. Second, industrial ecologists argue that natural ecosystems provide lessons for industry concerning the efficient use of materials and energy and the need to operate within the environment’s assimilative capacity for waste.⁶ Looking to the natural world for models that can be applied to industrial activity is the *biological analogy*, which is at the center of industrial ecology (Lifset and Graedel, 2002).⁷ For example, industrial symbiosis examines how

⁶ In this respect, industrial ecology is based on a philosophy that is similar to the biomimicry approach, pioneered by Benyus (2003), which involves learning from nature’s designs and processes to inspire innovation that can help to solve human problems. Biomimicry pays close attention to what can be learned from the way individual animals or plants function, such as how leaves may help us to invent better solar cells.

⁷ The comparison between industrial and natural systems is often considered to be a metaphor rather than an analogy. Ehrenfeld (2003) explains the importance of clearly distinguishing between

traditionally separate industries might exchange by-products for their mutual benefit.⁸ Thus, while industrial metabolism is a purely descriptive approach, industrial ecology also suggests how industrial systems should operate to become more sustainable (Korhonen et al. 2004). In particular, industrial ecologists seek to minimize reliance on end-of-pipe pollution control techniques by facilitating more comprehensive strategies for preventing wastes and emissions.

The field of industrial ecology is generally viewed as taking a multidisciplinary approach that includes economics and other social sciences, together with technical and environmental sciences. For example, Allenby (1999) identifies legal, economic, and other incentive systems to promote desirable behavior as part of industrial ecology. However, industrial ecology is largely dominated by scientists and engineers, and the literature does not fully incorporate the potential contributions economic analysis can make to improving environmental quality. As a result, industrial ecology tends to focus on descriptive studies that would likely benefit from greater consideration of economic dimensions. Similarly, one could argue that the emphasis industrial ecologists place on physical reality, life-cycle perspectives, biogeographical constraints, and ground truths could help to advance environmental and resource economics. This suggests that increased collaboration between economists and industrial ecologists has the potential to provide further insights into environmental improvement, environmental policy, and sustainability.

metaphor and analogy for industrial ecology, although he notes that industrial ecologists sometimes use the terms interchangeably.

⁸ The term symbiosis is taken from biology, where it refers to a close and persistent interaction between species.

The main objectives of this article are: (1) to introduce key concepts and techniques of analysis in industrial ecology; (2) to identify important developments at the intersection of industrial ecology and economics; and (3) to suggest areas for future collaboration and integration of the two disciplines. We recognize that reviewing the industrial ecology literature is a challenging task because industrial ecology is a rapidly growing field that is constantly evolving and that has no clearly defined boundary. Thus, a certain level of generalization in our analysis is unavoidable.

We begin in the next section with a discussion of two analytical tools commonly used by industrial ecologists – material flow analysis and life cycle assessment. Then we examine key efforts to incorporate economic analysis into industrial ecology and vice versa. This is followed by a discussion of how economics can further contribute to the tools, methods, and theories of industrial ecology, and thus help to address some of the limitations of the literature. We also critically examine from an economic perspective the biological analogy that is at the center of industrial ecology. The final section presents a summary and draws conclusions.

ANALYTICAL TOOLS OF INDUSTRIAL ECOLOGY

From an economic perspective, a complete system of Pigouvian taxes – which fully internalizes environmental externalities in market prices – can achieve efficient use of the environment by balancing marginal social benefits and costs. However, there may be barriers to achieving this optimal solution in practice. For example, legislative constraints may limit the use of Pigouvian taxes, thus forcing policy makers to consider

second-best solutions to environmental problems. Moreover, it is informationally demanding to establish the efficient Pigouvian tax rate for each good or service because it requires knowledge of the magnitude of external impacts, and many of these environmental externalities may be hard to identify and measure. This is where industrial ecology can help. By offering tools that quantify the amount of both direct and indirect emissions and solid wastes arising from economic activity, industrial ecology provides information that may help policy makers to design Pigouvian taxes or other market-based policies that successfully address environmental problems. Industrial ecology also provides information that can be used to enrich the empirical content of economic models and allow the analysis of economic-environment interactions.

Rather than attempting to provide an overview of all methods used in industrial ecology, this section examines the two analytical tools that are the most widely used by industrial ecologists: (1) material flow analysis and (2) life cycle assessment. Although these two tools have different objectives and data requirements, they both use a systems approach and the mass balance principle.

Material Flow Analysis

The objective of material flow analysis (MFA) is to track and quantify flows and stocks of a material (e.g., wood, glass, plastics) from source to sink, at a point in time and within a defined economic system. Substance flow analysis (SFA) is a specific type of MFA that involves analyzing the flows of chemical substances or compounds of

interest (e.g., carbon dioxide, phosphorous). MFA and SFA are based on a simple material balance that compares all inputs, stocks, and outputs of a process (Brunner and Rechberger, 2004). This approach makes it possible to establish a complete picture of material flows during extraction, production, use, and disposal. MFA and SFA can be applied on various spatial scales – such as national or regional, or along a particular industrial supply chain – and temporal scales.

By providing information about all flows and stocks of a particular material within a system, MFA can trace environmental impacts. In particular, it can provide information about potentially harmful accumulations and depletions of stocks, which can be used to identify unsustainable resource use. In addition, MFA may reveal previously unidentified sources of environmental externalities, such as leaching from landfills into soil or water (which can take place over a long time period). By looking at the whole system, MFA avoids the drawback of narrow, partial analyses, which might overlook important interrelationships or unintended consequences. Thus, the results of MFA can be used by designers and planners to conceptualize systems that may be less harmful to the environment than existing production and consumption practices.

Role of Economic Analysis in MFA

The MFA literature has generally focused on presenting the results of analyses, and methodological and model development issues, without identifying how results can be used to support actual policy and management decision-making. Thus, as concluded by Binder et al. (2009), MFA has a long way to go to reach its full potential as a policy-supporting tool. In addition, MFA studies do not usually model the economic

processes that drive material flows, or the implications of these flows for economic performance. Economic methods and tools could help to address these limitations by broadening the scope of the analysis beyond the environmental dimension, and considering how policies might be designed to implement the findings of MFA in practice.

The potential for economic analysis to broaden the scope of MFA can be illustrated by a case study. Chancerel et al. (2009) use SFA to assess the recovery options for precious and special metals used in electrical and electronic equipment at a German preprocessing facility.⁹ They find that only a tenth of the silver and a quarter of gold and palladium end up in outputs from which the precious metals can be recovered. Chancerel et al. (2009) then discuss the implications of their SFA for process optimization. For example, they suggest that manually removing the relevant materials (to avoid shredding them and dispersing part of the metal content) will reduce the loss of precious metals. Economic analysis could broaden this analysis by considering the economic costs of manual removal. In particular, are the benefits in terms of recovered metal value and reduction in environmental impacts worth the recovery costs? And if so, what tax or other policy options could be adopted to effect such a change?

Usefulness of MFA for economists

MFA may be helpful to economists seeking to analyze economy-environment interactions. For example, economy-wide MFA can be directly linked to the system of

⁹ This is a stage of the recycling chain which involves presorting, liberation through manual dismantling, and/or shredding and manual and/or mechanical separation.

national accounts, allowing for the construction of databases that integrate both environmental and economic information into one coherent accounting framework. This integrated approach is used by Eurostat (2017) to compile statistics on the relationship between GDP and the consumption of natural resources in the European Union. In addition, economy-wide MFA is a component of the United Nation's System of Environment-Economic Accounting (SEEA) international framework (UN, 2014), which is designed to facilitate the integration of environmental and economic statistics.

Life Cycle Assessment

Life cycle assessment (LCA) is a framework that tracks and quantifies the environmental impacts of a product across all stages of its life cycle – from the extraction of raw materials, to their manufacture, distribution, use, and maintenance, all the way through to the final disposal or recycling (and incorporating interdependencies between these stages). Here, the term 'product' can include both goods and services (ISO, 2006a). The attractiveness of LCA is that by taking a systems-based approach, it provides a comprehensive picture of the multiple parts of the system and the multiple environmental impacts. This differs from traditional environmental reporting, which is based solely on direct (in-house) impacts and does not include upstream and downstream impacts. Thus, LCA allows analysts to provide a more complete characterization of environmental trade-offs in product and process selection, helping firms and policy makers to more efficiently allocate resources to address environmental issues. For example, LCA can identify transfers of environmental impacts from one

media to another (i.e., transfers between air, water or land) or from one stage of the life cycle to another.

Components of LCA

LCA has become more systematic and robust over time due to the development of the International Organization for Standardization (ISO) standard for LCA (ISO, 2006a,b), as well as a range of supporting guidelines on managing and conducting LCA (e.g. UNEP, 2011; European Commission, 2010). Thus, LCA is now a mature tool with well-established methods. The ISO standard identifies four major components of an LCA study: (1) define the product or technology to be examined and the system boundaries of the analysis; (2) compile the life-cycle inventory (LCI), which is a detailed account of all energy inputs, material inputs, and environmental releases at each stage of the life-cycle scenario being examined (i.e., all exchanges between the human activity and its environment);¹⁰ (3) conduct the life-cycle impact analysis (LCIA) using the life-cycle inventory data and one or more assessment methods that translate inputs and emissions into human and ecological effects; (4) interpret, analyze, and communicate the results (ISO, 2006a).

Data demands of LCA

The LCI stage of LCA involves a detailed tracking of all flows into and out of the product system, and may involve numerous individual unit processes. Thus, it is a very resource intensive task. As a result, many databases have been developed to facilitate

¹⁰ Thus, while MFA typically focuses on a single material in many different products, LCI incorporates as many material inputs as possible that are associated with a single product.

the LCI stage and avoid duplication in data compilation (Finnveden et al. 2009).

Nonetheless, a system boundary for the analysis must be established because it is not practical to compile inventory data for all directly and indirectly connected economic processes. This means that environmental impacts that occur outside the system boundary will be omitted,¹¹ and if these impacts are important, the conclusions drawn from the LCA may be compromised.

One LCA approach that can help to overcome the demanding data requirements of LCI compilation is to focus on a single indicator, such as carbon footprint analysis¹² or cumulative energy demand (which considers only energy use). Reporting a single indicator is simple and intuitive, and thus is widely used by private companies, non-governmental organizations, and the media. While Weidema et al. (2008) recognize that a single indicator may in some cases be misleading, they argue that carbon footprints have increased consumer awareness and fostered discussions about the environmental impacts of products, which has promoted life-cycle thinking among policy makers and the general public.

Limitations of LCA

The relationships underlying LCAs are linear equations with fixed parameters that have been derived from empirical measurement. However, LCAs are usually steady state models and so do not include information on the temporal course of

¹¹ This is known as truncation error.

¹² In addition to carbon footprints, industrial ecologists consider ecological footprints (e.g., Barrett and Scott, 2001; Huijbregts et al. 2008) and water footprints (e.g. Gerbens-Leenes et al. 2009, Hoekstra and Chapagain, 2007).

emissions.¹³ In addition, LCA does not usually contain information about the geographical location of the emissions.¹⁴ This means that LCAs inherently assume a global set of average/standard conditions concerning the sensitivity of the receiving environment (Finnveden et al. 2009). Thus, when identifying the impacts of non-uniformly distributing pollutants, LCIA will overlook the possibility of large heterogeneities in environmental damage that depend on the location of the emission source. Another limitation of LCA is that it can yield different results when applied to the same product or service, and practitioners often do not consider the inherent variability and uncertainty in their results (Lloyd and Reis, 2007; Williams et al. 2009).

LCAs can also be criticized for not providing a clear decision rule for projects or policies. Although Ehrenfeld (2007) suggests that there are many examples of products that have used LCA information in their design, LCA results can be complex and difficult to interpret, and they ignore economic performance and social issues (e.g. social acceptance). Thus, LCAs are not helpful for prioritizing possible strategies, for either businesses or society (Ny et al. 2006). Later we consider how economists can help to address these limitations and ensure that LCA pays closer attention to economic considerations.

¹³ Recent studies that do consider temporal information in LCA include Levasseur et al. (2010), who examine an application to global warming, and Stasinopoulos et al. (2012), who develop a system dynamics approach to examine the production of automobiles. The literature on emissions from landfills also pays some attention to the time scales of different impacts (e.g., Hauschild et al. 2008).

¹⁴ However, several researchers have regionalized LCI and LCIA datasets (e.g. Steinberger et al., 2009; Sleeswijk and Heijungs, 2010. Also see Finnveden et al., 2009).

KEY COLLABORATIVE EFFORTS BETWEEN ECONOMICS AND INDUSTRIAL ECOLOGY

There have been some major efforts to incorporate economic tools and concepts into industrial ecology and vice versa, thus bridging the divide between the two fields. These have included the use of economic input-output models and the integration of market mechanisms into LCA. We discuss each of these efforts in turn.

The Use of Economic Input-Output Models in Industrial Ecology

Economic input-output models are naturally appealing to industrial ecologists because they provide an efficient accounting structure within a systems framework and are grounded in real world data. Following the seminal work by Duchin (1990, 1992), input-output analysis has been widely used to support the quantification of environmental interventions.¹⁵ LCA, in particular, has used input-output models extensively. An input-output LCA approach extends economic input-output tables to include data on resource use and environmental releases, which means that input-output LCA can quantify the material and energy flows through the complete supply chain of economic activity that is involved in producing the good or service (Lifset, 2009).¹⁶ LCA can also utilize a hybrid approach that combines conventional process-type analysis and input-output analysis.¹⁷

Input-output economics has also been used at the intersection of economics and industrial ecology to analyze resource challenges. One line of research uses an inter-

¹⁵ In particular, see the special issue of *Economic Systems Research* (Suh and Kagawa, 2005) and the *Handbook of Input-Output Economics in Industrial Ecology* (Suh, 2009).

¹⁶ This has the advantage of avoiding the truncation errors that can arise in a conventional LCA, which focuses only on a selected set of processes.

¹⁷ See Suh and Hupples (2005) for a more detailed discussion of these different LCA approaches.

regional input-output model of world trade – the World Trade Model (WTM) – developed by Duchin (2005). The WTM determines regional production, trade, and prices based on comparative advantage by minimizing factor use, where factors are measured in physical units. The WTM and various extensions have been used to analyze scenarios for sustainable development, including considering how trade adjustments can contribute to reducing global carbon dioxide emissions and the associated costs (Strømman et al. 2009); analyzing scenarios for satisfying future food requirements, including less resource-intensive diets and improved agricultural productivity (Springer and Duchin, 2014); exploring how economic comparative advantage in agricultural production changes in response to region-specific water endowments (Duchin and López-Morales, 2012); and analyzing the economic implications of restrictions on water withdrawals (López-Morales and Duchin, 2015). Duchin (2015) notes that the characteristics of input-output economics make it well suited for the analysis of emerging resource challenges, but that further theoretical work is needed to extend the scope of existing models, including the need to treat all potentially scarce resources as factors of production and to develop a framework for describing the endowment of such resources.

Integration of Market Mechanisms into LCA

Historically, LCAs have described the direct environmental impacts of a product's life cycle during a period of time, without considering indirect effects outside the specific product system being investigated – known as *attributional* LCA (aLCA). In

recent years, however, industrial ecologists have increasingly used *consequential* LCA (cLCA), which includes the effects of indirect, market-driven responses. More specifically, cLCA uses economic modeling to determine the effect that a change in production of a product has on the production and environmental impacts of other products.¹⁸ The market responses are not endogenized in cLCA; rather they are derived from economic models and then simply included as inputs into the LCA (Zamagni et al. 2012).¹⁹ In this way, cLCA considers not only the vertical dependencies in a product's supply chain, but also the horizontal linkages at each vertical step in that supply chain (Rajagopal, 2013). Initially, cLCA relied on simple partial equilibrium models. However, more sophisticated economic models have been used in recent years. For example, computable general equilibrium (CGE) models have been combined with LCA in various applications (e.g. Kløverpris et al. 2010; Dandres et al. 2011), and experience curves and learning effects have been integrated into cLCA (e.g., Sanden and Karlstrom, 2007).²⁰

cLCA and biofuels

To illustrate the potential usefulness of the cLCA approach, we examine the application of LCA to biofuels. A comprehensive carbon assessment of biofuels requires consideration of both direct and indirect land use changes. In the case of corn-based

¹⁸ Introduced in the 1990s, cLCA has become much more widely used over the last few years. See Earles and Halog (2011) and Zamagni et al. (2012) for reviews of the cLCA literature.

¹⁹ Ekvall (2002) refers to this approach of manually feeding the results of one model into another as softlinking. In contrast, hardlinking would combine the two types of models into a single model.

²⁰ Industrial ecologists are also developing extensions to the cLCA framework by incorporating endogenous market-driven design responses (e.g. Whitefoot et al. 2011). This reflects the fact that firms may have an incentive to adjust the design of their products in response to a change in a competing product's design.

ethanol, land use change can occur directly if those lands that have not been in continual crop usage (e.g., forests, grasslands, wetlands) are converted to corn production. There may also be *indirect* land use changes (ILUCs) because the diversion of corn into biofuels (and out of the market for food and animal feed) raises the price of corn, which in turn has spillover effects on the price and plantings of other agricultural commodities. These ILUCs cannot be modeled using the traditional aLCA approach, but cLCA can predict ILUCs by linking LCA with agricultural-economic models. However, the predicted amount and location of ILUCs vary greatly in cLCA studies on corn ethanol, which in turn leads to highly variable findings for greenhouse gas emissions. For example, Searchinger et al. (2008) find that U.S. corn ethanol production increases rather than decreases CO₂ emissions when ILUCs are included, but others dispute these findings (see Broch et al. 2013 for a review).

cLCA vs. aLCA

Although cLCA may have the conceptual advantage of identifying market-driven unintended environmental consequences, some industrial ecologists have warned that cLCA should not always be used over aLCA. For example, Dale and Kim (2014) question the usefulness of economic models and call for evidence that they provide reliable real-world predictions, while Suh and Yang (2014) argue that an idealized cLCA does not resemble a real-life cLCA. In addition, Zamagni et al. (2012) suggest that cLCA is not applied in a systematic and consistent way. In the future, economists should work with industrial ecologists to develop a more structured and

transparent approach for analyzing indirect economic consequences within a life cycle framework (see Rajagopal, 2017 for first steps in this direction).²¹

FUTURE OPPORTUNITIES FOR ECONOMISTS TO CONTRIBUTE TO INDUSTRIAL ECOLOGY

The previous section highlighted areas in which economics has already contributed to industrial ecology. Despite these collaborative efforts, industrial ecology continues to focus predominantly on descriptive or accounting exercises. This suggests that there is substantial scope for further collaboration between economics and industrial ecology, both on theoretical issues and in terms of providing practical guidance for environmental policy. In the previous two sections, we have identified some specific research and policy questions that economists can help industrial ecologists to address. In the discussion that follows, we synthesize these ideas and highlight the areas in which we believe economists should focus their efforts in order to have the greatest impact. These include using monetary valuation in LCA, broadening the scope of LCA, considering the role of economic incentives in the adoption of policy recommendations, and addressing conceptual limitations.

Monetary Valuation in LCA

LCA often shows that alternative decisions involve environmental trade-offs: one option may result in an improvement in one impact category relative to an alternative option, but cause deterioration in another impact category. In such situations,

²¹ However, economics may not be able to help address issues that involve the analysis of detailed, engineering-level phenomena.

identifying the preferred option requires normalizing the results relative to reference values (typically the total impact from all economic activities in the region of interest), and then weighting the scores according to their importance.²²

Monetary valuation techniques from the environmental economics literature have long been used for weighting in LCA. These valuation techniques can calculate the economic value of non-market impacts identified by LCA analysis, such as risks to public health, ecosystem services, or quality of life (such as opportunities for outdoor recreation).²³ The advantage of this approach is that monetary values are easily understood and allow complex effects and phenomena to be measured in the same units so they can be directly compared (Freeman et al. 2014).²⁴

In a review of monetary valuation methods in LCA, Pizzol et al. (2015) emphasize that there are several unique challenges to using monetary valuation methods in LCA, including the fact that LCA aggregates emissions and their impacts over the entire life cycle of the product. This means that LCA impacts have a high level of abstraction. Pizzol et al. (2015) find that although it is scarcely used, the choice experiment method²⁵ is the most appropriate method for the majority of LCA impact

²² The ISO's international standard includes normalization and weighting as optional final steps in the impact assessment of LCA (ISO 2006b). See Bengtsson and Steen (2000) and Finnveden et al. (2002) for a discussion of different weighting methods used in LCA.

²³ Valuation techniques calculate economic values based on individuals' willingness to pay for favorable impacts (or to avoid harm) or willingness to accept compensation for adverse impacts (or for the loss of an improvement).

²⁴ Many applications of monetization methods to LCA are conducted by industry without being published. For example, the Environmental Priority System (EPS) enviro-accounting method (Steen, 1999), which measures endpoint damage in monetary terms, is widely practiced by firms.

²⁵ The choice experiment method aims to identify the marginal value of the individual attributes of a non-market good on the basis of stated choices of respondents between alternative goods with different attributes.

categories. They also recommend the budget constraint method²⁶ to minimize uncertainty about the monetary value of a human life-year. They do not recommend the abatement cost method,²⁷ despite its use in many LCA applications, because it does not provide a valuation of damages. Given these findings, Pizzol et al. (2015) argue that there is considerable room for improvement in the use of monetary valuation in LCA.

Environmental valuation is a rapidly developing sub-discipline of economics, and substantial progress has been made in the development of techniques over recent years, especially concerning the valuation of ecological systems and services (see Freeman et al., 2014 and U.S. EPA, 2009). Thus, an important task for future research is for environmental economists to work with LCA practitioners to ensure that, where appropriate, recent advances in environmental valuation are fully incorporated into the industrial ecology literature.

Broadening the Scope of LCA to Better Inform Decision-Making

The valuation of environmental impacts allows LCA to assess environmental trade-offs. However, LCA considers only the environmental dimension of sustainability, and thus does not examine possible trade-offs between environmental and economic objectives. For example, although industrial ecologists are focused on moving toward a closed loop system for waste streams, which would reduce environmental damages, it may be costly to adapt and reorganize economic activity

²⁶ The budget constraint method involves deriving the marginal value of a Quality-Adjusted Life Year on the basis of potential annual economic production per capita.

²⁷ The abatement cost method assigns a price to an increase in emissions/damages that is related to the potential cost of a measure that prevents such an increase in emissions.

accordingly. This means that the environmental benefits to society of developing loop-closing systems may be offset by the costs of policy or design implementation.

Moreover, there may be alternatives to loop closing that also achieve a given reduction in waste discharges, such as input substitution, changing the production process, or changing the output mix. These measures are likely to have different cost profiles, which need to be included in the decision process in order to prioritize strategies. This suggests that in order to provide a normative or prescriptive framework for guiding real-world decision-making, industrial ecologists should move away from the biological analogy that is at the center of the industrial ecology paradigm – i.e., the use of natural ecosystems as models for industrial activity – and instead pay closer attention to economic opportunity costs. We next consider promising options for extending LCA to incorporate economic factors.

Combining LCA and supply chain management

One important way in which LCA can be incorporated into a broader framework is by applying it to supply chain management (SCM). SCM aims to improve the effectiveness and efficiency of a company's supply chain, and to ensure that the practices of upstream suppliers are aligned with the strategic goals of the firm. Because it focuses on sequential, linked sub-systems within an integrated whole, SCM has a similar pedagogical approach to industrial ecology. Firms engaged in SCM are often seeking to gain a competitive advantage, which means that SCM may include managing environmental concerns that threaten their reputation and operational performance. Thus, LCA has recently been incorporated into SCM in order to inform firms' managers

of environmental damage in the supply chain, which can be considered alongside other factors (such as cost, quality and/or security of supply).²⁸ Similarly, LCA can be used in assessments of procurement performance to identify purchasing criteria that are most effective in reducing environmental impacts. For example, this approach is used by Pelton et al. (2016) to identify procurement portfolios for a breakfast cereal firm that balance both economic and environmental considerations – i.e., that minimize environmental impacts based on LCA while meeting the firm’s budget and output requirements.

Combining LCA and life cycle costing analysis

Another promising approach that considers both the economic and environmental dimensions of sustainability is combining LCA with life cycle costing (LCC) analysis. LCC calculates the total costs of a product or process over its life span. These costs reflect all real monetary flows that are internalized in the decisions of the different actors in the product system.²⁹ Hoogmartens et al. (2014) note that LCC and LCA have similar structures, because they define system boundaries, time span, and functional units in the same way. LCC and LCA also share the same steady-state approach in which all variables are kept constant (e.g., technologies do not change); in addition, impacts are not discounted and double counting is avoided. This means that

²⁸ Seuring (2013) reviews the modeling approaches used in sustainable SCM, including LCA. Blass and Corbett (2018) consider issues that arise at the intersection of LCA and SCM.

²⁹ This type of LCC is sometimes called an environmental LCC (e.g., Hoogmartens et al. 2014), although it does not by itself include non-internalized environmental costs. By providing a code of practice, Swarr et al. (2011) take the first step toward the development of a rigorous methodological approach for LCC.

LCC can be fully integrated into LCA.³⁰ In order to balance environmental benefits and the economic costs, the impacts from LCA could be given a monetary economic value and aggregated with cost information from LCC. However, some researchers have argued that environmental valuations should not be aggregated with non-environmental costs (Reap et al., 2008). Nevertheless, even if one subscribes to the view that these values should not be aggregated, the results of LCC and LCA can still be combined to measure the cost-effectiveness of environmental benefits (i.e., a cost expressed per unit of environmental improvement or environmental improvement per unit of cost).³¹ Such indicators can also help policy makers interpret LCA findings and incorporate both economic and environmental factors into decision-making.

There have been only a limited number of analyses that combine LCC and LCA. Examples include Reich (2005), who assesses municipal waste management systems in Sweden; Simões et al. (2013), who compare two alternative materials for a storage tank; Ristimäki et al. (2013), who examine a district energy system for a new residential development in Finland; and Bi et al. (2017), who compare plug-in versus wireless charging of electric buses. Jeswani et al. (2010) note that the integration of LCC and LCA has been hampered by the lack of a standardized LCC methodology, as well as difficulties in defining some of the relevant costs and finding reliable and adequate data. Economists may be able to address these issues in future research. For example, economists could try to develop a general optimization framework that incorporates

³⁰ In contrast, as explained in OECD (2006) and Hoogmartens et al. (2014), it is not straight forward to integrate LCA and benefit-cost analysis (BCA).

³¹ For LCA this would still require that the results be normalized and weighted in order to obtain one single measure, but such a measure would not have to be monetary.

both LCC and LCA information, while ensuring that certain constraints (e.g., output requirements) are satisfied. A similar optimization approach has been studied extensively in the electric utility planning literature (e.g., Hobbs, 1995, and Parry, 2005).³² However, the focus need not be only on costs; methodologies might also be developed for incorporating other economic impacts (e.g., value added, innovation, productivity of labor and capital) along with LCA.

Addressing uncertainty

An obvious challenge for an approach that monetizes LCA results and integrates them with economic impacts is that it increases the complexity and uncertainty of the analysis. To address this challenge, economists can evaluate the uncertainty (e.g., confidence intervals could be constructed using the variance of the distribution) and present the findings to policymakers. In situations with multiple uncertainties, more advanced techniques (e.g., Monte Carlo methods, expert elicitations) may be necessary. Even if the uncertainty means that the analysis does not produce clear-cut policy recommendations, if the magnitude of environmental and economic impacts are included in the analysis, policy makers will at least have a better understanding of the trade-offs associated with alternative policy options.

Consideration of social impacts

In recent years, greater attention has been paid in the literature to social impacts throughout the life cycle of products. This has led to the establishment of *social* LCA,

³² This literature focuses on production, transmission and distribution of electricity, with emissions usually quantified as a linear function of the decision variables (Hobbs, 1995). In contrast, an LCA of electricity generation provides a detailed accounting of emissions and their related environmental impacts throughout the life cycle of electricity generation (see Turconi et al. 2013 for a review).

which considers *all* social impacts and damages to people (i.e., it is not restricted to damages from environmental impacts). Social LCA is a fast growing field, with researchers developing several methodological frameworks.³³ In addition, industrial ecologists have proposed combining LCA, LCC and social LCA to form a “Life Cycle Sustainability Assessment” or LCSA (Kloepffer, 2008; Valdivia et al., 2012).³⁴ The advantage of LCSA is that it provides a holistic, quantitative environmental assessment technique that combines economic, environmental, and social impact pathways in a structured and consistent way. However, Wood and Hertwich (2013) argue that LCSA should address *long-term* economic sustainability, not just the short-term economic costs reflected in LCC. Economic modelers are needed to develop the rigorous theoretical and empirical guidelines that LCSA practitioners need in order to meet this challenge. Thus, the participation of economists is essential to the success of the LCSA framework.

Developing Incentives for the Adoption of Policy Recommendations

Industrial ecologists tend to focus on engineering solutions to environmental problems. However, they have paid relatively little attention to the economic motivations of individual firms and consumers to adopt their recommendations in practice. Decisions made by private agents are often tied to particular objectives and are driven by economic incentives. If free markets do not provide incentives for firms or

³³ Fan et al. (2015) review various proposed methods; Mattioda et al. (2015) examine those that are the most influential in applications.

³⁴ See Jørgensen et al. (2013) for an analysis of the link between sustainability and life cycle methodologies.

consumers to act in an appropriate manner, then the incentive structure facing firms or consumers should be evaluated and, if necessary, changed.

Industrial ecologists rarely consider how the price mechanism can be used to address environmental problems. In fact, some authors argue that the whole point of comparing industrial systems to natural ecosystems is to move away from an individualistic perspective that is based on market incentives such as profit-maximization (e.g., Bey, 2001). Industrial ecologists are justified in their concerns about market failure. However, economists can draw attention to the insight that market-based policies such as emission taxes, emission trading, or technological subsidies, have the potential to ensure that prices reflect the true economic value of the resource or environmental amenity, where the full economic value includes both market and non-market values. Furthermore, such market-based policies provide incentives to firms to reduce their pollution levels in a cost-effective way. Thus, economists can help industrial ecologists to develop market-based policies that encourage private agents to adopt the recommendations from LCA and MFA.

Changing firm behavior

Firms will adopt environmentally beneficial technologies, or join together in material recycling, if doing so generates cost savings and is in line with strategic objectives. The empirical evidence clearly demonstrates the importance of market forces in industrial ecology. For example, Desrochers (2000) suggests that market incentives can account for most interfirm recycling. In addition, Lehtoranta et al. (2011) find that the main driver of industrial ecology initiatives in a Finnish pulp and paper mill is

financial gain, with regulation playing a smaller role. Despite these findings, few studies in the industrial ecology literature consider how environmental improvements can be achieved by using economic incentives to change firm behavior.

Changing consumer behavior

In terms of consumers, industrial ecology has long recognized the importance of consumer choice for sustainable consumption, and there is a well-developed literature on the environmental impacts of consumer behavior (Tukker et al. 2010). However, much less attention has been paid to changing consumer behavior, or what types of policy measures might stimulate sustainable consumer choices. Some recent studies have started to address this gap in the literature. For example, O'Rourke and Ringer (2016) assess how sustainability information might influence purchase decisions. In addition, in an analysis of residential lighting options, Hicks et al. (2015) examine the impact of policy interventions (such as an LED bulb purchase subsidy) on light and energy consumption. It would be helpful for economists to provide expertise and insight to facilitate further research along these lines. In particular, there is scope for much greater integration of behavioral economics into industrial ecology.

Addressing the Limitations of the Conceptual and Theoretical Foundations of Industrial Ecology

The conceptual foundation of industrial ecology is centered on the biological analogy. This analogy arose because of the similarities between industrial systems and natural systems; for example, both are characterized by flows of material and energy between components. However, the biological analogy can be misleading because the

structures, processes, and dynamics of biological and industrial systems are fundamentally different. In the discussion that follows, we highlight the limitations of the biological analogy and consider a more appropriate framework for industrial ecology that economists could help to develop further.

Differences in the structure of economic and natural systems

Ayres (2004) notes that economic systems produce heterogeneous outputs of goods and services, while a natural ecosystem does not produce products, but rather more of itself, along with wastes and dead matter. In addition, natural systems have no markets, no medium of exchange (like money), nothing analogous to paid labor, and interactions are involuntary. Levine (2003) points out the relative absence of products in ecological systems leads to a number of other important differences. For example, in ecological systems, material flows are supply (or input) driven,³⁵ and involve interactions that are predatory (i.e., beneficial to one party but detrimental to the other) or commensal (i.e., one party benefits while the other is not affected). In contrast, industrial systems are largely demand, or output, driven, and interactions only occur when mutually beneficial for both parties. Thus, the biological analogy is insufficient for a rigorous analysis of material and/or energy flow relationships throughout the economic system.

Natural evolution versus economic change

³⁵ Each organism in the food chain strives to capture as much energy as they can from the previous (lower) trophic level in the chain.

Another drawback of the biological analogy is that biological evolution is different from changes in economic systems. In the natural world, structures are simply the product of evolution according to a natural set of rules (natural selection and random mutations). In contrast, humans can be active in driving change via conscious decision-making. Economic selection is driven by competition, while diversity arises due to discovery, invention, and innovation (Ayres, 2004). Therefore, humans are unlike natural ecosystems in that they can foresee both risks and opportunities, and plan ahead accordingly (Johansson, 2002).

Establishing a coherent theoretical framework

Because of the differences between industrial and natural systems, industrial ecology should aim to progress beyond the notion of the biological analogy, and to refine and formalize theories into physically and mathematically robust principles. Based on a coherent theoretical framework, industrial ecologists should then develop empirically testable hypotheses, and perform successful tests. To properly understand industrial systems, the focus should be on developing models with an empirical grounding in economic behavior. Thus, a greater input from economists can help to develop the literature further in this direction.

Some industrial ecologists have supported this approach. For example, Jackson and Clift (1998) call for a coherent theory of agency so as to identify individual actors and whether the profit incentives are in place to encourage them to act appropriately. Building on this, Andrews (2000) explains that industrial ecology would benefit from building a micro foundation that distinguishes individual humans from firms, and

incorporates behavioral evidence about human agents into the conceptual foundation. In addition, Andrews (2000) believes that theory should focus on the role of transaction costs and recognize the information problems involved in transactions in order to reconcile normative and empirical perspectives. This approach can help to identify how to alter behavior within social networks and tell us more about how to develop a sustainable industrial system. Economists could expand on this approach to provide a theoretical foundation for the industrial ecology literature that is more suitable than the biological analogy.

SUMMARY AND CONCLUSIONS

The central aim of industrial ecology is to understand and improve the environmental performance of industry. Industrial ecology takes a systems approach to the analysis of material and energy flows, thus bringing a holistic approach to tracing environmental impacts. This article has provided an overview of the field of industrial ecology, considered developments at the intersection of industrial ecology and economics, and identified a number of areas where economists can make further contributions.

Industrial ecology requires a combination of experts to provide a comprehensive framework for sustainability assessment. We have shown that some economic methods and techniques have been integrated into the industrial ecology literature, notably in the form of input-output LCA and consequential LCA. However, economists remain underrepresented in this rapidly growing field and many industrial ecology studies

continue to be essentially environmental accounting exercises, with no basis for setting priorities and little consideration for economic-environmental trade-offs or how to implement policy recommendations in practice. Moreover, the biological analogy at the center of industrial ecology has serious shortcomings, and the discipline lacks a theoretical foundation that can provide a basis for the formulation and testing of hypotheses. We have emphasized the important role that economists can play in helping to overcome these limitations. Thus, future collaborations between economists and industrial ecologists are needed to ensure that industrial ecology achieves its full potential as a policy-supporting tool.

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