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Article

From Theory to Practice: Enhancing the Potential Policy Impact of Industrial Ecology

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Abstract: Industrial ecology introduced a new paradigm of principles and tools useful to academic analysis and decision support activities for industry and policymakers. This paper presents a view of the state of the art of industrial ecology, encompassing the four major theoretical traditions comprising the field, and emphasizing the relevance to practice. The principles of industrial ecology offer a basis for integrating environmental perspectives into production and consumption strategies, though there are significant challenges to be addressed.

Keywords: industrial ecology; industrial symbiosis; natural ecosystem metaphor; engineering system metaphor; social science approach; system theory approach; impact

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1. Introduction

Industrial ecology (IE) is a flourishing multi-disciplinary science attracting academic and policy attention from a global community. Resting on the assumption that human impact on the environment needs to be reduced, and that lessons on how to do that can be learned from natural ecosystems, industrial ecology concerns the flows of materials and energy that comprise the industrial ecosystem, and the scientific, technical, economic, political, social and cultural issues related to those flows [1].

The policy relevance of industrial ecology is currently very high. The related concept of the circular economy (with aims including keeping resources economically active e.g., by recycling) is official policy in China [2]; and has been announced as a governing principle of resource management in the EU [3] Elsewhere, both developed (e.g., Japan [4]) and increasingly developing countries are establishing relevant policies, for example, based on extended producer responsibility (e.g., Thailand [5]). Life cycle analysis (LCA), a tool widely studied and practiced within IE, is recommended by the United Nations as a means to promote sustainable production and consumption [6]. The tools and resource practices associated with IE are also highly relevant in terms of carbon emissions reductions [7]. The policy context is of great relevance to academics in several respects. Policies can provide the constraints within which an IE tool is applied; may create a demand for such a tool; or may themselves be the object of critical analysis. However, academic research is increasingly required to demonstrate an economic and political relevance. This potential for "impact" as termed in the UK [8] is a criterion by which research proposals (and project outputs) are judged. Moreover, impact in this sense is almost the *raison d'être* of the European Union Horizon 2020 research funding programme [9] It is timely, therefore, to illustrate the connections between the theoretical, academic approaches to IE and policy applications.

An overview of the four major theoretical traditions within IE is followed by a brief discussion of emerging themes. The review is based primarily on work accessed through the Web of Science™ that identifies itself as industrial ecology. We make no claim to be comprehensive on either the past or present scope of the field. Rather, we hope to provide an overview useful to those who may be new to IE, or unaware of its scope, as well as providing our perspective on current developments, and their potential policy impact.

2. Theoretical Themes in IE

There are several key lines of theoretical enquiry within the realm of industrial ecology. Debates are underway within these regarding theoretical developments, research methods, adapting methods for practical application, and lessons to be learned from case studies. These theoretical pathways comprise discussion, first, around the biological metaphor between human–industrial systems and natural ecosystems; second, what might be seen as an engineered system metaphor, which (alongside ecological economics) has sought to apply the principles of thermodynamics to human–industrial systems; third, the application of systems theory to solve problems relating to such systems and fourth the development of theory to explain industrial systems drawing on social science approaches. Each theoretical approach drives a tool or key method. These approaches are outlined in turn, before a brief discussion of emerging issues and their potential impacts.

2.1. Natural Ecosystems Metaphor

The idea that human society could reduce its impact on the environment by learning from nature is fundamental to IE [10,11], helping to establish the identity style and scope of the field. Learning from the web of interrelationships within natural ecosystems, analysis and optimization of and resource use should not focus on the scale of individual organisms (e.g., companies, production facilities), but rather on a system scale (whether defined as a product, process or place). The ecosystem scale focus provides a number of concepts that have been considered with respect to industrial systems [12] such as system diversity [13]), and resilience [14,15].

A predominant idea within IE, derived from the ecological metaphor, is that of the desirability of an industrial ecosystem, *i.e.*, community of companies exchanging unwanted substances (as in industrial symbiosis theory). Resource use is thereby optimised at the scale of the (eco)-system rather than individual companies [16]. A particular instance of this would be an eco-industrial park, *i.e.*, a group of co-located companies comprising an industrial ecosystem [17]. Jensen *et al.* [11] have called for a reappraisal of IE, rightly asserting that IE has been selective in its choice of lessons from ecosystems. Enthusiasm for the metaphor generally came from engineers rather than biologists; the appropriateness of drawing the comparison has been extensively discussed [18,19]. Jensen *et al.*'s proposed analysis of existing industrial practice and interrelationships ("the ecology of industry" [11] (p. 683)) could be complementary to the existing, more normative approaches to resource efficiencies, consistent also with a more critical appraisal of when and whether ideas derived from the biological metaphor might be environmentally beneficial [20].

A second idea is that, like organisms, individual goods have a life cycle (production, use, disposal) distinct from product life cycle (innovation, design, manufacturing, obsolescence) [21]. Analysis, and minimisation, of environmental impact should therefore take into account the full life cycle ("cradle to grave", or "cradle to cradle"). System-scale analysis requires system scale measurement tools. Life cycle analysis (LCA) is one such, which has been predominant within IE [22,23]. LCA is a means of recording the inventory of impacts (material/energy/water use, gaseous, liquid or solid emissions), from which the relative environmental impact of alternative processes, products or system configurations can be derived [24]. It is not directly a measure of environmental impact. An environmental scientist's approach to environmental impact assessment is quite distinct from that of an industrial ecologist assessing life cycle environmental impact. The environmental scientist looks at how ecosystems or components thereof respond to anthropogenic signals [25]. LCA is a measure of the dimension of that signal, not a measure of how it might be received.

2.2. Engineered Systems Metaphor

An engineered system comprises a set of interacting objects performing a specific function; characteristically they have well defined boundaries, with components that behave in a predictable and controllable fashion [26]. This is not to imply that such systems cannot be technologically sophisticated and complex. The study of systems (as distinct from applying systems theory, as discussed below) has been a fundamental component of IE. Whereas the biological metaphor has been introduced to IE and applied by non-biologists, the interest in engineered systems has come from engineers and scientists for whom they are the norm. Consequently, perhaps, there has been relatively little discussion of the suitability of this approach, compared to the discussion around ecosystems.

In addition to the adoption of system-scale analyses such as LCA, engineering has also yielded its own concepts to IE, notably the application of the principles of thermodynamics. Thermodynamics refers to the relationship between heat, energy and ability to do work within a system, be it open or closed [27]. These laws are important as they describe the physical limits on the work that can be done by an ideal system (with the term "exergy" used sometimes for available work [28]). The energy available in a real system is further limited by a dissipative loss of energy e.g., as friction-generated heat. The study of thermodynamics was a response to nineteenth century efforts to develop and increase the efficiency of engines [27]. It doubtless remains essential in the design and analysis of systems where heat flow is present [29,30], such as the study of a technology to capture waste heat in cement kilns [31]. As flowing or embodied materials can be expressed as embodied energy or exergy, this could be a convenient measure to combine or compare relative impacts of life cycle impacts of potentially quite different things [22]. Suetens *et al.* [32], for example, conducted an exergy-based LCA of arc furnace dust treatment technologies. There is, however, a trade-off between simplicity and complete information.

Another fundamental scientific principle relevant to IE relates to the conservation of mass in a closed system. This principle produced an interest in material balance in economic systems that substantially pre-dates the origin of IE as a concept in science or industry [33,34]. Material flow accounting (or analysis) (MFA), and input–output analysis (borrowed from economics), are widely applied tools in IE that assess the flows or material and/or energy into and out of systems, or which add to or draw from stocks of the relevant type within the system [35]. MFA can be applied at different scales and over different time periods. Schaffartzik *et al.* [36] for example, used MFA to calculate the raw material equivalent of Austrian consumption between 1995 and 2007. On a longer timescale, Krausmann *et al.* [37] traced the material flow history associated with the industrialisation of Japan between 1878 and 2005, whereas Lifset *et al.* focus on US copper flows from 1975–2000 [38]. Thermodynamic analysis can also be combined with MFA, which, as with LCA, can help to overcome the challenges of different data availability for materials and energy [15]. On a simple level, MFA is distinct from LCA, as the former measures flows between social-economic units of the economy (including nation states) and the latter assesses the magnitude of exchanges between such units and the environment. The two tools can be applied in conjunction with each other and/or with input output analysis [39,40], though with due care to prevent the double counting of impacts [41].

Tools for measuring flows or their impacts within or between systems have certain core issues in common. These include defining the system boundaries, which in socially mediated systems, or even in biological ecosystems, may be a lot less objective than in an engineered system (e.g., a building heating management system). Once analysis has gone beyond the scale or scope of a purely technical system to consider a system that has people as a component (e.g., from appraisal of the theoretical efficiency of building heating management systems to consider the use of such a system), boundaries are more blurred and the level of control vastly diminished. It may be uncertain who, if anyone, is actually in control [26]. Data availability and reliability are also key limitations [34,41,42], constraining the level of detail for a given study and the ability to compare with other studies. Such issues, however, take analysis beyond the realm of purely engineered systems into that of the social sciences.

2.3. Social Science Approaches

Over the last decade, social science contributions to IE literature have seen a marked increase [23]. This work in part addresses concern over the lack of awareness of social processes displayed by some engineering approaches to IE [43]. Socially mediated systems cannot be controlled like engineered systems and organizations (individually or in combination) cannot be expected to behave like organisms. Social systems are prone to the imperfect knowledge, at best bounded rationality of decision makers, and vulnerable to uncontrollable events [26,43]. Social science methods have been used to analyse the approaches used to implement industrial ecology, most particularly in the field of industrial symbiosis (IS). Early work has served as a significant check on the optimism of industrial ecologist academics and practitioners that eco-industrial parks could readily serve as a means to implement IE on a local scale [44,45].

However, more recently, successful examples of various forms of IS have emerged in a wide range of policy/geographic contexts (e.g., Australia [46], China [47], Netherlands [48], Portugal [49], Puerto Rico [50], Japan [51], South Korea [52], the United Kingdom [53]). Study of the role of policy context in IS has become more explicit [54], with the need emerging for an understanding of the key elements of IS, in order to avoid a context dependent definition [55].

Following the identification of successful examples of IS (both planned and "uncovered" in the terms of Chertow [56]), industrial ecologists have applied the tools of quantitative analysis to them. Chertow and Miyata [57] and Eckelman and Chertow [58] respectively apply LCA and MFA to an industrial symbiosis network in Hawaii. Social scientists have also begun to theorise the development of IS networks. Spekkink and Boons [59] have used both quantitative and qualitative methods to explore institutional capacity [60] as a concept to explain IS development. A significant thread of work has appeared exploring IS networks through social network analysis (SNA). SNA examines the relationships and interactions between the actors (or stakeholders) in a given network, emphasising the "social embeddedness" of the phenomenon [61,62]. IS, or other material and/or technical arrangements, do not form independently of social processes and structures. Potential network participants, for example, need access to information from a source they trust before they can even consider entering into a resource exchange. Much of this is in response to the UK IS network facilitated by the National Industrial Symbiosis Program (NISP) (e.g., [53,63]) and a related regional network [64]. A significant exception is Ashton and Bain's application of SNA in the emerging economy context of India [65].

Some of these social science approaches are drawing on systems theory in a more or less explicit way. Although it overlaps with both engineering and social science approaches, systems theory needs to be addressed as a distinct field.

2.4. Systems Theory Approaches

Whilst engineering tools are designed for studying at a system scale, this is distinct from applications of systems theory. Strongly influenced by the work of von Bertalanffy [66], and ultimately also inspired by biological systems, systems theory does not attempt to learn from nature in the sense of the ecosystem metaphor. Inspired also by the complexity of twentieth century technology and associated social organization [67], systems theory "provides a framework by which a group of interrelated components that influence each other can be analysed. That group can be a sector, branch, city, organism, or even a society" [67] (p. 185). The social, or human, element of the system is explicitly studied, in contrast to the engineering approaches, in which the decision making happens outside of the analytical process. An LCA, for instance, is done on a given scenario, or set of scenarios; the results may be invaluable to policy makers, but the decision making processes and politics behind scenario definition and selection is outside of the scope of the study (e.g., [68]). Conversely, a systems approach may aim to bring about change, *i.e.*, resolve a particular problem [22,69].

A recent and currently small thread of literature is applying systems theory to IE systems, inspired by an interest in complexity theory, or Complex Adaptive Systems (CAS) [12,67]. A CAS is characterised by open boundaries; the system can adapt and evolve in response to stimuli via the self-organised interactions between components (actors or stakeholders in a social system). Relationships between the diverse components are constrained by hierarchical organisational structures (e.g., multi-level governance of environmental policy making). The field covers a wide range of approaches from highly quantitative modeling related to the engineering systems tradition, through quantitative social science approaches to highly qualitative social science that, for example, explores the subjectivity of stakeholder behaviour [70]. The first two approaches can be found in IE. For example, Romero and Ruiz use game theory to apply agent based modelling to assess strategies for developing industrial ecosystems [69]. Schiller *et al.* present a method to combine both social and material network analysis in order to capture both the social and technical aspects of industrial ecosystem development [64].

3. Emerging Debates

Arguably, the key assumption of industrial ecology is that economic benefits can be gained from environmental efficiencies [71]. This has been questioned from different perspectives such as the relative costs and benefits from a resource exchange for different stakeholders [72]. However, economic benefit, in the sense of security of supply of resources may put a new complexion on debates of environmental impact. IE’s primary approach to resource conservation has been to extend the economic use of materials that have already been extracted or manufactured (e.g., via recycling and IS).

Northey *et al.* [73], for example, caution that whilst copper reserves do not appear to be in immediate danger of exhaustion, they could be significantly depleted in the next 20 years. Conventional LCAs may not offer policymakers suitable information on which to base a decision with scarcity implications [35]. Valero and Valero [28] present an exergy-based LCA approach which tries to address that deficiency by considering, for example, the energy implications of using an alternative to the depleted resource in question. However, framing an LCA to prioritise supply of a scarce resource (e.g., to maximise metal recapture from recycling), may discount the environmental impact of relevant processes [74]. Tools such as LCA or MFA especially in isolation, may offer limited guidance for complex subjective decision making (e.g., in urban metabolism applications of IE tools [75]).

One attempt to adjust LCA for the implications of social assumptions is to make explicit the incorporation of the social implications of scenarios under consideration [21]. This has been a significant development in recent years. Expanding an LCA into a sustainability LCA attempts to adapt the process to a tool for sustainable development (which should therefore consider issues such as inter- and intra-generational equity) rather than a tool for environmental protection [21,35]. Adapting the diverse aims of sustainability to a normative form suitable for an analysis akin to LCA is a challenging task in and of itself, which furthermore greatly expands the data needed and expertise both to compile and assess the outputs of the analysis [76]. Authors have incorporated sustainability considerations in to a range of LCA applications. Neugebauer *et al.* focus their sustainability analysis in terms of social justice, using education and wages as a measure of equity and opportunity [77]. Stefanova *et al.* consider the framing of a sustainability LCA in the context of hydrogen production from biomass [78]. Norris *et al.* are concerned with the availability of data for social analysis of products in a supply chain context [79].

A key tension in the engineering approaches to IE is between the need for improvements on the one hand (e.g., data quality, scope of study) and the need for usability on the other. The concerns of policy and company-based applications of IE tools differ from each other as well as from those of academics devising and applying tools [24,80,81]. However, a number of authors are working on precisely the area of increasing the suitability of IE tools for practical application [82]. Arzoumanidis *et al.* [83] present a simplified LCA for use in the wine production sector, whilst Cappelletti *et al.* [84] apply LCA to olive oil production focusing on energy requirements. The tool has also been applied to the fishing industry [85]. The system-scale perspective of IE can itself present challenges. Companies can clearly most readily enact sustainability measures within their own purview, as considered by Despeisse *et al.* [81].

IE research has clearly responded to the climate change imperative within environmental discourse and policy making. Numerous studies have appeared within IE highlighting the utility of its tools for emissions management [86–91]. Linder and Guan [90], for example, use a hybrid IO-LIA to calculate the embodied energy and life cycle emissions for goods consumed in China. The hybrid approach is considered to better represent emissions at the scale of an economy, as opposed to e.g., a product, and therefore should provide information more directly relevant to policymakers. Similarly, Pauliuk *et al.* [88] combine techniques from MFA and LCA in order to take account of indirect emissions from households in their study of residential emissions and energy usage in Norway. Related to the interest in GHG emissions is research into biomass (including bio-waste) as a fuel. Singh *et al.* [92] present an LCA of different technologies for biomass-based transport. Other recent examples include Muradin and Foltynowicz's [93] examination of the potential for biogas production from agricultural waste in Poland, in addition to the paper by Stefanova *et al.* [78] mentioned above.

The combining of IE tools (e.g., LCA, MFA and IOA) has been brought about in part by the need to adjust the scope of the system analysed to incorporate consumption (or indirect) environmental effects as well as production for a given territory [40]. Analyses need to take into account the fact that goods consumed in a given territory may have been produced elsewhere, and therefore would not be included in the inventory of production-related environmental impacts for the territory. This shift, or expansion, of interest from production to consumption environmental impacts has been a component in the appearance of studies at the urban scale [94,95]. Stremke *et al.* [96] proposed the application of thermodynamic principles found in IE to urban planning. A related line of research explores water supply, transport and the environmental impact of other such technologies of collective provision [97,98]. Extending the study of IE to consumption effects away from the home, Lucchetti and Arcese examine applications of IE to tourism [99], linking IE applications to eco-tourism planning actions [100].

Notwithstanding the breadth of approaches within IE, both its theories and tools need to acknowledge and engage with alternative approaches, especially where established in practice. Ioppolo *et al.* present preliminary observations based on an analysis of both lean management and IE. This provides a possible assessment of the key factors relevant to synthesize a "lean environmental management" [101]. In addition, the Product Oriented Environmental Management System (POEMS) represents an integration of IE and supply chain management principles to improve the environmental performance of products and organizations. The POEMS offers an approach to addresses both policy sustainability goals and growing consumer interest in sustainable productions (e.g., [102,103] in the agri-food sector).

Recent work in social science approaches to IE has also engaged with theories developed beyond the field. Institutions, for example, have been identified as important elements in the implementation of IE.

Pajunen *et al.* analyse the institutional and legal barriers to IS relating to both domestic and EU waste regulations in Finland [104]. Combining institutional analysis with consideration of deliberative environmental policy, Levanen and Hukkinen examine how actors mentally adjust to changes in the formal rule structure [105]. They analyse how the meeting of the two aspects of institutions (formal rules and social norms) can serve as a guide to environmental policy design. The stakeholders, their interrelationships, materials, technology and regulations involved in implementing IE (including IS) are a prime example of what has been termed a socio-technical system. There is considerable literature on socio-technical systems and associated sustainability transitions management, which is applied to IE by Rotmans and Loorbach [67]. Also exploring the transitions perspective, Vernay *et al.* [106] draw on actor network theory to analyse the integration of traditionally separate systems (sewage disposal and transport) in a Swedish case study. Shi and Li assess how eco-industrial parks in China have become more of a mainstream than niche development [7]. Placing more emphasis on the specifics of place and the interconnections of industry with that place, or territory, than is usually the case in IS literature, Dumoulin and Wassenaar explore the building of symbiosis links between companies drawing on the French concept of “territoire” [107].

5. Conclusions

IE is a thriving and highly robust field of academic enquiry. It is extremely broad in both empirical focus and research methodology, albeit the preponderance of contributions stems from the quantitative, engineering side of the discipline [23]. As a highly policy-relevant field, IE could make a significant impact on policy and practice in the coming years. There are, however, a number of challenges to be overcome within the discipline before it can fulfill its potential to engage with the wider community.

A multi-disciplinary field, IE contains a range of tools useful for the integration of environmental concerns across a wide range of applications (e.g., [102]). A prominent feature of emergent research and policy themes is the need, and willingness, to cross the divide between the theoretical traditions of IE. There is an increasing recognition of the role of people in what may appear purely technical systems and also that decisions about systems (technical or otherwise) impact on people in different ways. One example of this is the increasing interest in sustainability LCAs. Notably, though, putting social factors into a quantitative model does not change the nature of the exercise—people as decision makers are still outside of the system of analysis. To address the stakeholders, or actors, within a system requires a different approach, as illustrated by work in the social science tradition. This is not to argue for the prioritisation of one type of study over another; each has a role in describing, understanding and explaining the nature of the industrial ecosystem, providing a continuous improvement to and widening of IE applications.

Further developing the policy and practice relevance of IE will also require a great understanding of the constraints on, and geographic context of, non-academic IE stakeholders. Discussion of policy context has often been understated in the IE literature [54]. However, this cannot sensibly be overlooked in considerations of IE implementation, or theorisations of practice, in different locations. Context is also highly relevant to understand the potential for possible new fields of application of IE (e.g., the aspects of eco-system services related to water resource management in China [108]). The disparity of requirements of different types of users of IE analyses has created a degree of tension in the field. The demand for more complex, precise, LCA, for example, and/or more broadly defined systems is countered by the need for pragmatic adaptations of IE tools that non-experts can understand and implement. This of course itself provides opportunities for research: not produce pragmatic approaches but to assess the implications of compromise, both in terms of effectiveness and for the development of the discipline.

There are of course aspects of IE to implement beyond the scope of academia which have significant influence. These issues should be a focus of social science IE research. However rigorously and precisely IE tools are applied, they are not value-free exercises [21,35]. Multiple decisions lie both behind the framing of a scenario (or establishing the scope of an analysis) and in deciding whether or how to respond to the results. These decisions may be political (*i.e.*, involve a choice between conflicting interests) and/or economic (e.g., influenced by affordability or marketing potential) rather than primarily environmental (e.g., addressing potential environmental impact). Economic imperatives are difficult for industry to overlook, but political intervention can change the context of decisions, e.g., to make IS a more favourable option than simply disposing of industrial residues [109]. It is an exciting time to be working in the field of IE. We look forward to observing and contributing to developments over the coming years, in this and other journals, as the field strives to increase its impact in practice whilst maintaining academic momentum and critical independence.

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Author Contributions

Relative contribution of the authors is indicated by order of listing. Both authors framed the discussion in accordance with an initial idea of Giuseppe Ioppolo; Pauline Deutz carried out the literature search and wrote the first draft. Both authors edited and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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