Geography Compass 2/4 (2008): 1138–1154, 10.1111/j.1749-8198.2008.00123.x

Industrial Symbiosis and Eco-Industrial Development: An Introduction

David Gibbs*
Department of Geography, University of Hull

Abstract

In recent years, industrial ecology has been the subject of both academic and policy interest, as a means of implementing sustainable development. For some academic researchers, industrial ecology is seen as the 'science of sustainability', while for policy-makers one aspect of industrial ecology, industrial symbiosis, has seemed to offer new opportunities to combine environmental improvement, economic development and local regeneration through the construction of eco-industrial parks. Industrial symbiosis uses metaphors drawn from natural ecosystems to suggest that industrial production can be reconfigured into an 'industrial ecosystem' where firms are interconnected through the exchange of wastes and energy. This article is intended to provide an introduction to some of the key ideas involved in industrial symbiosis and to the ways in which it has been used to inform policy.

Introduction

A concern for the environmental consequences of economic development appears to have become a permanent feature of the social and political landscape. Although these concerns pre-date the event itself, the Rio Earth Summit of 1992 played a key role in putting these environmental concerns onto national and international political agendas. One of the legacies of Rio has been the widespread adoption of sustainable development as the basis of environmental policies. Instead of assuming that economic development and environmental protection are inevitably incompatible, proponents of sustainable development argue that it allows the integration of economic, environmental and social aims. However, while sustainable development is now a mainstream component of policies around the world, its actual implementation is more problematic. How exactly can economic, environmental and social aims be reconciled and what kinds of measures should policymakers introduce? In the early 21st century, these questions have taken on even greater importance with a growing recognition of the impacts that can result from enhanced global warming. Changing weather patterns and sea level rise as a consequence of global warming are now generally accepted as fact by the majority of scientific opinion and by politicians.

Table 1. Definitions of industrial ecology.

Definition	Source
[Industrial ecology aims] to develop a more closed industrial ecosystem, one that is more sustainable.	Frosch and Gallopoulos (1989, 94)
Industrial ecology . . . is a systems view in which one seeks to optimise the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product and to ultimate disposal. Factors to be optimised include resources, energy and capital.	Graedel and Allenby (1995, 9)
Industrial ecology takes a systems view of the use and environmental impacts of materials and energy in industrial societies. It employs the ecological analogy in several ways, including analysis of materials flows.	Andrews (1999, 366)
. . . use nature's model of material recycling, energy cascading and solar energy-based sustainable ecosystem in transforming unsustainable, fossil fuel-based and wasteful industrial systems into more ecosystem-like systems	Korhonen et al. (2004)

Even politicians in the USA, long the major climate change deniers, appear to have accepted it as scientific fact, even if they remain reluctant to commit the USA to binding international measures for carbon reduction strategies.

It is against this broader context that we can see why the concept of industrial ecology (IE) has begun to enter into both academic and policy debates. In the 1990s, industrial ecology emerged as a concept that its proponents claim can deliver the win–win–win outcome of sustainable development (see Table 1 for some definitions). Ashford and Côté (1997), for example, term it a new unifying principle to operationalise sustainable development. Industrial ecology encompasses a range of topics, including design for the environment, eco-efficiency, material and energy flows as well as the main focus in this article – industrial symbiosis.

> Industrial ecology is principally concerned with the flow of materials and energy through systems at different scales, from products to factories and up to national and global levels. Industrial symbiosis focuses on these flows through networks of businesses and other organisations in local and regional economies as a means of approaching ecologically sustainable industrial development. (Chertow 2004, 1)

At the heart of the concept of industrial symbiosis is a deceptively simple argument that proposes a way to reduce or eliminate the negative impacts of economic development – by drawing on the example of natural ecosystems we can create 'industrial ecosystems'. By mimicking nature, industry can shift from the current wasteful linear model of production to a circular economy, where natural resource inputs are reduced, wastes transformed into firm inputs and energy cascaded through the industrial ecosystem. The use of natural metaphors has been a powerful motivating factor that has captured the imagination of both policymakers and developers. To take just one example, promotional material for the Red Hills EcoPlex in Mississippi states: 'Still think of "industrial park" as synonymous with "smoke stack", "pollution" and "expensive eyesore"? Fortunately it's time to think again . . . the EcoPlex mimics a natural, efficient ecosystem' (see McManus and Gibbs 2008, for a critique of the use of natural metaphors in industrial symbiosis). Industrial symbiosis differs from more commonplace efforts to 'green' industry in that it fosters cooperation between firms as opposed to focusing on action at the level of the individual firm, seeing firms as nodal points within a networked ecosystem. By cooperating with each other in an industrial ecosystem, it is proposed that businesses can improve their combined environmental performance by measures that will also increase profit margins.

Industrial symbiosis has increasingly developed as an academic subject, with its proponents drawn mainly from two broad disciplinary bases – engineering and business and management studies. Some of the latter group have added an additional benefit to be gained from policies to encourage industrial symbiosis – the regeneration of local areas and social gains through employment (Schlarb 2001). Interestingly, few biologists or ecologists have been involved in these debates; although, in a rare example, Harte, a physicist and ecologist, has argued that natural ecosystems provide a poor model for designing business systems on the basis that the former are inherently unstable, wasteful and lack any moral direction (see Harte et al. 2001). Industrial symbiosis has also entered into the policy arena, with a growing number of local, regional and national initiatives to try and create industrial ecosystems in some form. Hence, eco-industrial parks, regional industrial symbiosis projects and national circular economy strategies have all appeared in recent years (see Mirata 2004; Tudor et al. 2007; Fang et al. 2007, respectively, for details of these). Certainly, a key part of any future move towards a 'less unsustainable' society will necessitate major shifts in the way that industry operates. The prospects for this are open to substantial debate, given that the profit-driven organisation of production has been known to constrain some shifts towards sustainability. Indeed, authors such as O'Connor argue that capitalism inevitably degrades the ecological conditions it depends on – the second contradiction of capitalism (O'Connor 1998). Thus, a tendency towards ecological crisis may therefore be just as endemic to capitalism as a falling rate of profit or over-accumulation. However, while mindful of the problems involved in overcoming the ecological contradictions of capitalism (see Gibbs 2006), industrial symbiosis approaches may help to provide at least a temporary fix and involve 'relative (but significant) changes into more environmentally sound directions' (Mol 2002, 97).

With very few exceptions, there has been little acknowledgement of these developments and debates in the geographical literature (though, see Desrochers 2002, 2004; Gibbs 2003; Gibbs and Deutz 2005, 2007; Gibbs et al. 2005; McManus 2005; Randles 2007). In this article, I provide a general introduction to the ideas of industrial symbiosis for a general audience and try to draw out some of the areas that might be of interest to geographers. The structure of the article is as follows: in the next section, I define and describe industrial symbiosis in more depth. Following this, I then turn to an outline of the ways in which industrial symbiosis has been incorporated into policy prescriptions, especially in the form of eco-industrial parks. Finally, I assess the future prospects for industrial symbiosis, as both policy idea and academic subject.

Defining Industrial Symbiosis

A central argument within industrial symbiosis is that the environmental impact of industry can be reduced by learning from an analogy with natural ecosystems. In natural ecosystems, the energy and/or matter produced by one species is consumed by another. In industrial processes, by contrast, surplus heat is commonly dissipated in the atmosphere and potentially recyclable by-products are disposed of as wastes. While it has been argued that both industrial ecology and industrial symbiosis have longer histories (see Erkman 1997 and O'Rourke et al. 1996, for historical accounts of their development), the terms were popularised in a seminal work by Frosch and Gallapoulos (1989) in an article for *Scientific American*. As opposed to comprising isolated components in a system of linear flows, they saw processes and industries as interacting systems. The essence of industrial symbiosis is that there will be interactions between, and interdependence of, ecosystem components, compared with the emphasis on independence and competitiveness in a more traditional view of industrial systems. Côté and Cohen-Rosenthal (1998), for example, emphasise the importance of relationships between actors in industrial symbioses. This provides a basis for thinking about ways in which various waste producing processes, plants and industries can be connected into a network of exchange to minimise the amount of industrial material currently going to disposal sinks or lost in intermediate processes. Frosch and Gallapoulos went on to make an analogy with the food web and suggested that industrial ecology has potential as a means to conserve raw material by minimising waste on the scale of an industrial ecosystem, not just at the level of the firm. Thus, by contrast with conventional approaches that emphasise waste minimisation from an individual process or facility (i.e. pollution prevention), the focus is on waste minimisation of the larger system as a whole (Brand and de Bruijn 1999; Richards et al. 1994). While impacts at the level of the individual firm or process remain important, these are seen as connected to a wider industrial ecosystem. In industrial ecology, these firm or process impacts are addressed in the parallel concept of industrial metabolism, which is concerned with the efficiency of the metabolic processes within species individuals (or in this case firms or processes) (Ayres 1989). Improved industrial metabolism across the whole spectrum of industrial processes would, it is argued, make the creation of industrial ecosystems easier (Tibbs 1992). Thus, 'a better understanding of material flows is a first step to increasing the eco-efficiency of society's metabolism by closing material flows into loops of recycling and reuse' (den Hond 2000, 61). In industrial ecosystems, effluents and wastes from one process serve as inputs for other processes or are recycled for further production, mimicking food webs in natural systems (Dunn and Steinemann 1998). Subsequent researchers have developed these analogies further. In another ecological parallel, it is proposed that 'niche species' will emerge to fulfil functions, for example, through the formation of new enterprises to transform wastes into useful inputs or new products. Dunn and Steinemann (1998) suggested that, just as species exploit niches in the food chain, such companies would exploit niches in industrial ecosystems – as waste scavengers, for example. These firms would use opportunities in material reprocessing to recycle what are conventionally seen as 'wastes' into new products. An example of this can be seen at the Ecosite du Pays de Thau in southern France where a number of spin-out companies have been formed to exploit synergies enabled by technologies developed onsite. Marine micro-algae are fed on nutrients from the sewage treatment process at the Ecosite and themselves processed for use in a variety of applications, including pharmaceuticals, cosmetics and food (Gibbs and Deutz 2007). Industrial symbiosis, therefore, represents a shift away from dealing with localised environmental impacts in isolation through measures such as clean technologies and eco-efficiency, which reduce material inputs and reduce wastes at the level of the firm (Lovins et al. 1999; Organisation for Economic Cooperation and Development 1998). It is argued that industrial symbiosis therefore offers a holistic conceptual framework for the kind of 'significant, systemic industrial change' needed to eliminate environmental damage (Tibbs 1992, 1).

Korhonen (2001) identifies four principles of industrial ecology. The first of these, which he terms 'roundput' to distinguish it from linear forms of industrial production, comprises the most commonly cited features of industrial symbiosis – materials recycling and energy cascading. He then extends the biological analogy to include: diversity, for example, of species or economic actors; locality, for example, use of natural resources, local cooperation; and gradual change, for example, a slow rate of development of system diversity. Andrews (2001) adds a scale dimension to the ecosystem analogy, suggesting that an attention to micro-scale activities; in this case, the behaviour and motivation of individuals, may offer a practical way forward for industrial symbiosis. However, while in natural ecosystems the largest flows in the producer-consumer-recycler system are from producers (plants) to recyclers (micro-organisms, bacteria, decomposers, fungi, etc.), in current industrial systems flows from both producers and consumers to recyclers are on a small scale (Korhonen 2001). As already stated, the extent to which the ecological analogy can be pursued is open to question, but researchers into industrial symbiosis make a valid point that the current linear organisation of industrial production fails to recover much post-production, let alone post-consumption materials. In an ideal industrial ecosystem, there would be complete or nearly complete internal recycling of materials and energy, effectively the achievement of 'zero discharges'. In reality, most commentators realise that 'the vision of a perfect industrial ecosystem will never happen' (Korhonen 2002, 41), but that it is worth pursuing as a policy goal (Allenby 1999).

Many of its proponents argue that industrial symbiosis is one way to implement sustainable development (Allenby 1999; Cohen-Rosenthal 2003; Frosch and Gallapoulos 1989; President's Council on Sustainable Development [PCSD] 1997). As Burström and Korhonen (2001) argue:

> [T]he environmental benefits . . . are to be found in the reduction of virgin material and energy inputs to the industrial system, and of waste and emission outputs from the system. In a successful *industrial ecosystem* the economic gains lie in the reduction of raw material and energy costs, waste management costs and cost resulting from environmental legislation, as well as the improvement of 'environmental image' and 'green market' potential.

Similarly, Dunn and Steinemann (1998) outline the ways in which the sustainable development agenda can be advanced through industrial symbiosis. They argue that in economic terms waste 'roundput' has benefits for all parties involved through reducing waste disposal costs and also the costs of raw materials. Environmental gains are simultaneously achieved by a reduction in both waste production and the exploitation rate of new resource inputs. The social gains from industrial symbiosis are more tenuous, with some authors suggesting that increased company profitability will have trickle-down effects on both local spending and jobs to the benefit of the wider local population (Schlarb 2001). A major objective within the industrial symbiosis agenda is therefore to engender a fundamental paradigm shift in the organisation of industry–ecology relations (den Hond 2000; Wallner 1999). This will not be achieved over the short to medium term, rather:

> [T]he result of an industrial ecological approach over time will be a gradual overall transition, taking several decades, to an eco-industrial infrastructure, so that all process systems and equipment, and plant and factory design, will eventually be built to interconnect with industrial ecosystems as a matter of course. (Tibbs 1992, 24)

Implementing Industrial Symbiosis: Eco-Industrial Development

Although industrial ecology has been described as the 'science of sustainability' (Allenby 1999), the field is still in its early stages. Moreover, much academic and policy work has so far been largely speculative, theorising what could be done to create an industrial ecosystem. The one example of what could be achieved that is cited time and again in the literature is the

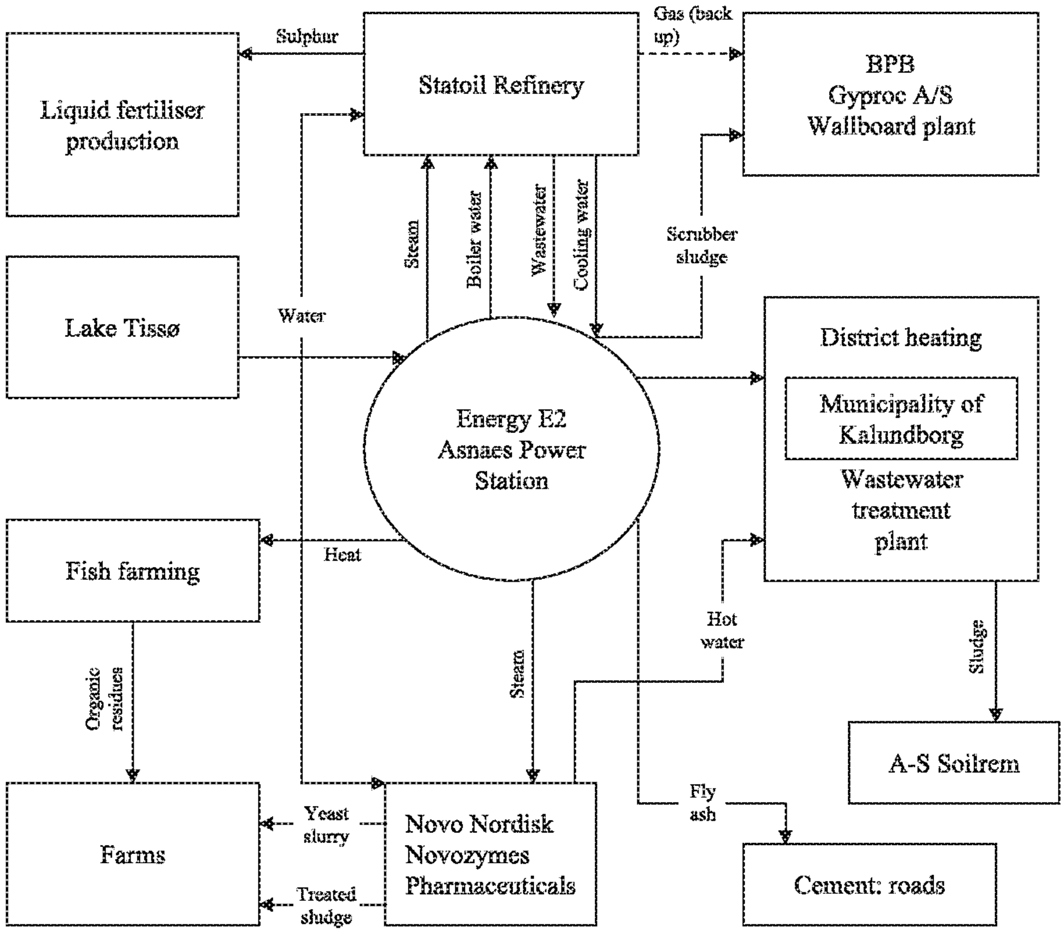

Fig. 1. Industrial symbiosis at Kalundborg.

town of Kalundborg in Denmark. Given that anyone interested in exploring industrial symbiosis further will inevitably meet references to Kalundborg, it is worth outlining the main features of the example (see Jacobsen 2003, for more details and www.symbiosis.dk for the official website). At Kalundborg, a web of waste and energy exchanges developed connecting the local city administration, a power plant, a refinery, a fish farm, a pharmaceuticals plant and a wallboard manufacturer (Figure 1). The power plant generates electricity by burning refinery gas and steam production, sending excess steam to a fish farm, the city and the pharmaceuticals plant. Residual steam is also piped to the refinery by the power company which, in exchange, receives refinery gas previously flared as waste. Nearby, farms use sludge from the fish farm and the pharmaceutical processes as fertilisers. Power plant fly ash is used by a cement company, while gypsum produced by the power plant's desulphurisation process goes to a company producing wallboard (Brand and de Bruijn 1999). It is estimated that waste exchanges at Kalundborg comprise some 2.9 million tons of materials each year, collective water consumption has been reduced by 25% and the power station has reduced water use by 60% through recycling (Chertow 2004).

For many working in the field of industrial symbiosis, the example of Kalundborg has seemed to offer support for their ideas. Here, voluntary cooperation between individual companies and other participants has developed organically over time to create something like an industrial ecosystem. For some, this indicated that if such a system could develop organically, much more might be achieved through purposeful planning. For example, Hawken (1993, 63) after musing on the lessons from Kalundborg states 'imagine what a team of designers were to come up with if they were to start from scratch, locating and specifying industries and factories that had potentially synergistic and symbiotic relationships.' Indeed, Kalundborg is frequently cited as the industrial symbiosis exemplar in the literature and has often been used to justify policies to establish industrial symbiosis projects – for example, the four eco-industrial demonstration sites designated by the US PCSD (Martin et al. 1998). The example of Kalundborg was an important factor behind the establishment of a task force on eco-industrial parks (EIP) by the PCSD in the USA in the early 1990s. In conjunction with the Environmental Protection Agency and the Department of Energy, the PCSD designated four EIP demonstration sites in 1994 – at Baltimore, MD; Cape Charles, VA; Brownsville, TX; and Chattanooga, TN (Martin et al. 1998). While these sites are still frequently mentioned in the industrial symbiosis literature as being current (see Oh et al. 2005), only Cape Charles became operational and even this site had abandoned any EIP principles by the early 2000s (Gibbs and Deutz 2007). From the late 1990s onwards, a consensus emerged that the creation of EIPs at specific bounded locations could be a valid means of implementing industrial symbiosis and achieving Hawken's aim of a planned Kalundborg. An initial definition of an EIP by leading US practitioners was:

> A community of manufacturing and service businesses seeking enhanced environmental and economic performance through collaboration in managing environmental and resource issues including energy, water, and materials . . . the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realise if it optimised its individual performance. (Lowe and Warren 1996, 7–8)

The PCSD used a similar definition to Lowe and Warren, with the inclusion of the local community as both a contributor to resource flows and a beneficiary of environmental and economic improvements. Various local and regional projects have subsequently been initiated to plan and actively develop EIPs in the USA, Europe, Asia and Australasia (see among others Business Council for Sustainable Development 2002; Chiu and Yong 2004; Eilering and Vermeulen 2004; Erkman and Ramaswamy 2003; Heeres et al. 2004; Lowe 2003; Mirata 2004).

Much debate has been engendered within the industrial symbiosis community as to whether developments that involve interactions among member businesses and between them and their natural environment (i.e.

Table 2. Eco-industrial development strategies.

- Resource recovery, pollution prevention and cleaner production
- Materials and energy interchanges
- Integration into natural ecosystems
- Industrial clustering
- Sustainable/green design
- Anchor tenant
- Life cycle assessment
- Job training
- Environmental management systems
- Deconstruction and de-manufacturing
- Technological innovation and continuous environmental improvement
- Public participation and collaboration

Source: Schlarb (2001).

by-product exchanges or symbioses) are a defining feature of EIPs. For Lowe (2002, 2), 'the critical elements are the interactions among the park's member businesses and the community's relationship with its community and natural environment.' Lowe (2002) is essentially concerned with the end product of EIP development and does not consider features such as 'green architecture', landscaping features or a cluster of recycling companies as constituting a valid EIP. In contrast, other authors suggest that an incremental approach to EIP development should be adopted. For example, North and Giannini-Spohn (1999, cited in Schlarb 2001, 12) argue that EIP development can involve a 'palette of strategies for increasing resource efficiency. While the ideal EIP or IE network would incorporate all of these strategies in the long-term, companies participating initially might add strategies incrementally as the business case for each becomes stronger.' Indeed, Schlarb (2001, 1) suggests that although the 'unique contribution [of eco-industrial development] is its emphasis on inter-firm exchange linkages', there are a number of other strategies that can be adopted to promote resource efficiency (Table 2).

Some of the features listed in Table 2, such as job training and public participation, could well be present once an EIP became operational, but they are not specifically eco-industrial strategies in themselves. Other features are part of the broader industrial ecology field (e.g. life cycle assessment, pollution prevention) that might be adopted by some EIP companies, but do not necessarily contribute to the inter-firm cooperation characteristic of industrial symbiosis (Chertow 2000). Some elements of Table 2 can be deliberately incorporated into EIP design, such as landscaping and the sustainable design of buildings. Others, such as resource recovery or deconstruction and de-manufacturing, could be adopted either by individual firms or form a theme for an EIP. An anchor tenant (a term derived from the experience of shopping mall development) could act as a central feature of an EIP and a step towards establishing symbioses. Having an anchor tenant would help to define potential sources of exchanges (e.g. the use of steam from a power plant or waste heat from a chemical plant). In addition, it was thought that the availability of specific by-products from anchor tenants may attract potential EIP tenants (Chertow 2000).

In adopting an incremental approach, while materials and energy interchanges may be the ultimate goal of EIPs, given the difficulty of achieving these they should perhaps be seen as a medium to long-term target, rather than the defining feature of the initial development. Some authors have suggested that the development of exchanges and networks can not be introduced through policy and are best left to market forces (Desrochers 2002) and that EIP development is an overambitious task (Chertow 1999). Chertow (2000, 322) also cautions against considering waste exchanges and traditional recycling industries as evidence of industrial symbiosis as they 'accomplish various input/output savings on a trade by trade basis, rather than continuously'. Whereas Lowe (2002) dismisses a collection of bilateral exchanges as inadequate to warrant definition as an EIP, Chertow (2000) proposes establishing bilateral exchanges within an EIP as an initial step, as opposed to trying to establish a complex network from the outset.

As is evident from this brief overview, there is considerable debate over what defines and constitutes an EIP and on how industrial symbiosis can be implemented. While it is possible to be sympathetic to the argument that creating industrial symbiosis is a long-term and incremental process, it can be argued that some degree of waste and energy exchanges and inter-organisational networking must eventually be present by definition. In the absence of these, suggesting that all of the elements listed in Table 1 are broadly similar seems to lack any critical engagement. As O'Rourke et al. (1996, 90) argue this would mean industrial symbiosis 'is vague and broad enough to serve as the catchword for many different arguments.' This is not to suggest that networking and interchange are easy to develop or that Kalundborg can readily be replicated through policy. In the next section, I outline some of the difficulties that have been experienced with developing eco-industrial projects through policy.

Industrial Symbiosis: Problems and Prospects

As industrial ecology has developed as a discipline, it has become apparent that 'a large gulf separates descriptions of what IE can be, and specific examples and strategies for implementing IE' (O'Rourke et al. 1996, 94). This is especially true for industrial symbiosis and EIP developments, which have been among the most visible and high-profile attempts to implement aspects of industrial ecology. Although only a limited amount of empirical work has been undertaken, the evidence suggests that little or no networking and firm interchanges are occurring, even at those EIPs cited in the literature as prime exemplars of the genre (see Eilering and

Vermeulen 2004 and Heeres et al. 2004 on the Netherlands and the USA, and Gibbs and Deutz 2005, 2007 on US and European examples). Despite the best efforts of planners and developers, a 'planned Kalundborg' has yet to develop, with an additional gulf between the expectations raised by this example and the probability of recreating it. Perhaps we should not be surprised by this – expecting firms to relocate to a site specifically to procure secondary materials is unrealistic when the 'minor importance of waste costs and relatively low costs of attaining secondary materials' (Sterr and Ott 2004, 949) means that these play a small part in firms' location decisions, at least in developed countries. By-product flows will only be crucial to location decisions if they are the most important inputs for a firm (Desrochers 2004).

This disjuncture between ideals and reality clearly underlies the frequently made observations on the difficulty of putting industrial symbiosis into practice. The difficulties of implementing industrial symbiosis have subsequently spawned a debate among researchers in the field as to whether developments that involve interactions among member businesses and between them and their natural environment (i.e. by-product exchanges, resource partnerships or symbioses) are a defining feature of EIPs (see the journals *Journal of Industrial Ecology* and *Progress in Industrial Ecology*). As outlined above, some have argued that an incremental approach is needed, whereby interactions come at the end of a long process of the adoption of pollution prevention measures, energy efficiency measures, 'green' architecture and resource recovery, etc. (North and Giannini-Spohn 1999; Schlarb 2001). Similarly, it has been argued by EIP developers that implementing industrial symbiosis is likely to be a long-term process that may come about only after other eco-industrial elements have been introduced at a site (Gibbs and Deutz 2007). From this incremental perspective, while materials and energy exchanges may be the ultimate goal of EIPs, given the difficulty in achieving these they should perhaps be seen as a medium to long-term target rather than as a key part of the initial development strategy. Again, while sympathetic to the idea that EIPs need to develop over time through a variety of strategies, it can be argued that waste and energy exchanges and some form of inter-organisational networking *must* eventually be present to earn this definition. Given that the industrial symbiosis literature is largely premised on networking and interchange behaviour, suggesting other features can define industrial symbiosis or EIPs runs the same risk of ambiguity as is commonly found with sustainable development. As Eilering and Vermeulen (2004, 249–250) argue: 'We can only call an eco-industrial park sustainable when sustainable symbioses in relation to the environment are evident.' Any long-term vision for EIPs must reflect the emphasis on networking and collaboration and should be in a real sense a community of, and not just colocated, businesses. It is this networking activity that will potentially encourage materials interchange in the long term and distinguish eco-industrial developments from other, more superficial, initiatives for the greening of industry.

While collaborative behaviour between firms is central to eco-industrial development if the potential benefits of industrial symbiosis are to be realised, it is important to recognise that such behaviour is difficult to develop from scratch through policy intervention. Trust and co-operation need to be developed between firms before they are prepared to link processes together in ways that have an impact on the economic viability of the firm (Gibbs 2003). However, although it has been argued (see Desrochers 2004) that interchanges are best left to the market, corporate managers often have neither the time nor the ability to appreciate the commercial opportunities that industrial symbiosis may offer (Esty and Porter 1998). Policy intervention could therefore play an enabling role in helping to identify these opportunities and creating the appropriate conditions for inter-firm networking to take place. In such cases, 'local authorities could serve as network brokers and "institutional anchor tenants" initiating the actor networks and providing political and managerial support as well as informational and educational services and infrastructure support for the other participants of the industrial ecosystem' (Korhonen et al. 2004, 299). In situations where an environmental culture and inter-firm networking are not present, third-party organisations may help to facilitate these through proactive involvement (Wasserman 2001). Even then, there may be conflicting views within a locality as to the most appropriate use (and users of) wastes – we cannot assume that all the actors (small and large firms, households, farmers, public sector workers, politicians, etc.) have the same interests (Korhonen 2004b). Moreover, there may be regulatory barriers that discourage the development of symbioses. For example, in the USA, the *Resource Conservation and Recovery Act* and its definition of hazardous wastes are felt to discourage re-use of waste streams, and changes to national legislation may be necessary to facilitate EIP development. Similarly in the UK, waste management regulations are believed to inhibit symbiotic relationships building up due to regulations on storage and definition of wastes (Gibbs and Deutz 2007). Of equal importance in both cases, however, would appear to be motivational barriers on the part of private sector firms to become involved with networking and materials interchange activities.

Indeed, one issue that must be taken into account is the extent to which firms are willing or able to conduct such local exchanges. In relation to willingness, much may depend on specific organisational cultures within an area. Low levels of inter-firm cooperation in an area, even among firms in the same sector, may engender a culture which is not conducive to exchanges. Even when economic advantages are pointed out to firms, the costs involved may not be sufficient to alter behaviour or individuals may simply be unwilling to change their behaviour patterns (Sterr and Ott 2004). Conversely, existing social networks may help to encourage environmental networking through forming mutual trust. In relation to ability, as Korhonen (2004a, 816) notes, we also need to know 'how much of the product life cycle is retained within the local/regional boundaries'. Attempting to engender inter-firm linkages assumes that the spatial extent of (at least some of) the constituent firms' operations are congruent with the local area. In reality, however, there may be a spatial mismatch between the two, such that linkages are difficult to engender. Those firms that are subsidiaries of national or transnational corporations are more likely to be part of their wider corporate network than embedded in local transactions. Moreover, they may have limited decision-making powers onsite and be unable to alter materials linkages (Randles 2007). For individual firms, the territorial limits and market size of an EIP are usually too small to guarantee continued existence, as Sterr and Ott (2004) show in their study of Heidelberg-Pfaffengrund in Germany. The question, therefore, arises as to the appropriate scale for any industrial ecology project – if the industrial park or 'the local' is not the appropriate scale, perhaps more be achieved at the regional scale, building on existing industrial regions? These kinds of questions have led some industrial symbiosis researchers to suggest that more might be achieved through building on existing industrial regions rather than trying to create parks *de novo*. Thus, Chertow (2007), in an analysis of 15 'planned' and 12 'self-organised' industrial symbiosis projects, suggests that planned projects have rarely been successful. In contrast, pre-existing self-organizing systems are more successful in generating symbiotic exchanges although they are 'never mapped and described using ecological metaphors' (Chertow 2007, 20). Chertow goes on to argue that 'uncovering' such pre-existing industrial ecosystems and then building on these through public policy intervention is a more fruitful task than establishing new EIPs. Indeed, this type of approach has gained greater currency as a policy tool. For example, the National Industrial Symbiosis Programme in the UK takes a regional approach to developing symbioses, with industrial symbiosis animateurs working closely with firms to identify potential synergies and exchanges in workshops (for details, see www.nisp.org.uk).

Finally, there is a broader set of questions relating to industrial symbiosis and the extent to which it should be seen as anything beyond a means of reducing the impact on the environment by industry. The argument that developing EIPs can not only bring about environmental improvement and improved economic performance, but also has the potential to act as a source of economic development and job creation in depressed areas created substantial interest from policymakers (for example, see the collection of papers in Cohen-Rosenthal and Musnikow 2003). Schlarb (2001) argues that industrial symbiosis has moved from a technologically driven approach, focusing on resource exchanges, to a broader look at systems and networks, involving non-material exchanges, to a third stage involving community-based interactions. If this is so (and actual evidence for this is lacking), then it raises questions about the definition of industrial symbiosis being used. In approaches such as that of Schlarb, industrial symbiosis becomes a social construct, such that it encompasses virtually any form of networking and interconnection between businesses, the community and the public sector, not just materials recovery and interchange. This is substantially different to original conceptions of industrial symbiosis. Indeed, using the industrial symbiosis concept seems to place a substantial additional burden on such developments, raising high expectations of creating another Kalundborg and extending the idea substantially beyond the more modest aims of its original proponents. The danger could be that the failure of EIPs to live up to the over-inflated expectations of developers and policymakers could mean that industrial symbiosis becomes seen as a blind alley. However, while this may eventually prove to be the case, there is considerable scope for more research into the role of industrial symbiosis as one component of broader attempts to reduce the environmental impacts of economic development, not least in many of those countries that now dominate actual physical production of goods, such as China.

Acknowledgements

Thanks to Gary Brierley and two anonymous referees for their helpful comments on an earlier version of this aricle. All errors and omissions remain the responsibility of the author. The support of the Economic and Social Research Council (Grant number R000239428) is acknowledged.

Short Biography

David Gibbs is Professor of Human Geography and Director of the Graduate School at the University of Hull, Hull, UK. He has held visiting posts at Macquarie University, Monash University and the University of Cincinnati. His research interests are in the field of local and regional economic development, with a particular focus on the interplay between economic development and the environment. He is the author of number of journal articles on these topics, of the book *Local Economic Development and the Environment* (Routledge, 2002) and co-editor of *The Sustainable Development Paradox* (Guilford, 2007). Recent research projects have included ESRC-funded work on 'Sustainability and the Local Economy: The Role of Eco-Industrial Parks' and 'Governance and Regulation in Local Environmental Policy Making'.

Notes

* Correspondence address: David Gibbs, Department of Geography, University of Hull, Cottingham Road, Hull HU6 7RX, UK. E-mail: d.c.gibbs@hull.ac.uk.

References

Allenby, B. R. (1999). *Industrial ecology: policy framework and implementation*. Englewood Cliffs, NJ: Prentice Hall.

Andrews, C. (1999). Putting industrial ecology into place: evolving roles for planners. *Journal of the American Planning Association* 65, pp. 364–375.

——. (2001). Building a micro foundation for industrial ecology. *Journal of Industrial Ecology* 4 (3), pp. 35–51.

Ashford, N. A., and Côté, R. P. (1997). An overview of the special issues (on industrial ecology). *Journal of Cleaner Production* 5 (1/2), pp. i–iv.

Ayres, R. U. (1989). Industrial metabolism. In: Ausubel, J. H. and Sladovich, H. E. (eds) *Technology and environment*. Washington, DC: National Academy Press, pp. 23–49.

Brand, E., and De Bruijn, T. (1999). Shared responsibility at the regional level: the building of sustainable industrial estates. *European Environment* 9, pp. 221–231.

Burström, F., and Korhonen, J. (2001). Municipalities and industrial ecology: reconsidering municipal environmental management. *Sustainable Development* 9, pp. 36–46.

Business Council for Sustainable Development. (2002). *National industrial symbiosis programme, business delivery of political strategy on resource productivity*. North Sea Region: BCSD.

Chertow, M. (2000). Industrial symbiosis: literature and taxonomy. *Annual Review of Energy and Environment* 25, pp. 313–337.

——. (2004). Industrial symbiosis. *Encyclopedia of Energy* 3, pp. 1–9.

——. (2007). 'Uncovering' industrial symbiosis. *Journal of Industrial Ecology* 11 (1), pp. 11–30.

Chertow, M. R. (1999). The eco-industrial park model reconsidered. *Journal of Industrial Ecology* 2 (3), pp. 8–10.

Chiu, A. S. F., and Yong, G. (2004). On the industrial ecology potential in Asian developing countries. *Journal of Cleaner Production* 12, pp. 1037–1045.

Cohen-Rosenthal, E. (2003). What is eco-industrial development? In: Cohen-Rosenthal, E. and Musnikow, J. (eds) *Eco-industrial strategies: unleashing synergy between economic development and the environment*. Sheffield, UK: Greenleaf, pp. 14–29.

Cohen-Rosenthal, E., and Musnikow, J. (2003). *Eco-industrial strategies: unleashing synergy between economic development and the environment*. Sheffield, UK: Greenleaf.

Côté, R. P., and Cohen-Rosenthal, E. (1998). Designing eco-industrial parks: a synthesis of some experiences. *Journal of Cleaner Production* 6, pp. 181–188.

den Hond, F. (2000). Industrial ecology: a review. *Regional Environmental Change* 1 (2), pp. 60–69.

Desrochers, P. (2002). Industrial ecology and the rediscovery of inter-firm recycling linkages: historical evidence and policy implications. *Industrial and Corporate Change* 11, pp. 1031–1057.

——. (2004). Industrial symbiosis: the case for market coordination. *Journal of Cleaner Production* 12, pp. 1099–1110.

Dunn, B. C., and Steinemann, A. (1998). Industrial ecology for sustainable communities. *Journal of Environmental Planning and Management* 41 (6), pp. 661–672.

Eilering J. A. M., and Vermeulen, W. J. V. (2004). Eco-industrial parks: toward industrial symbiosis and utility sharing in practice. *Progress in Industrial Ecology* 1 (1/2/3), pp. 245–270.

Erkman, S. (1997). Industrial ecology: an historical view. *Journal of Cleaner Production* 5 (1–2), pp. 1–10.

Erkman, S., and Ramaswamy, R. (2003). *Applied industrial ecology: a new platform for planning sustainable societies*. Bangalore, India: Aicra Publishers.

Esty, D. C., and Porter, M. E. (1998). Industrial ecology and competitiveness: strategic implications for the firm. *Journal of Industrial Ecology* 2 (1), pp. 35–43.

Fang, Y., Côté, R. P., and Qin, R. (2007). Industrial sustainability in China: practice and prospects for eco-industrial development. *Journal of Environmental Management* 83, pp. 315–328.

Frosch, R., and Gallopoulos, N. (1989). Strategies for manufacturing. *Scientific American* 261, pp. 94–102.

Gibbs, D. (2003). Trust and networking in inter-firm relations: the case of eco-industrial development. *Local Economy* No. 18, pp. 222–236.

——. (2006). Prospects for an environmental economic geography: linking ecological modernisation and regulationist approaches. *Economic Geography* 82 (2), pp. 193–215.

Gibbs, D., and Deutz, P. (2005). Implementing industrial ecology? Planning for eco-industrial parks in the USA. *Geoforum* 36, pp. 452–464.

——. (2007). Reflections on implementing industrial ecology through eco-industrial park development. *Journal of Cleaner Production* 15 (17), pp. 1683–1695.

Gibbs, D, Deutz, P., and Proctor, A. (2005). Industrial ecology and eco-industrial development: a new paradigm for local and regional development? *Regional Studies* 39, pp. 171–183.

Graedel, T., and Allenby, B. R. (1995). *Industrial ecology*. Eaglewood Cliffs, NJ: Prentice Hall.

Harte, J., et al. (2001). Business as a living system: the value of industrial ecology (a roundtable discussion). *California Management Review* 43 (3), pp. 16–25.

Hawken, P. (1993). *The ecology of commerce*. New York: Harper Business.

Heeres, R. R., Vermeulen, W. J. V., and de Walle, F. B. (2004). Eco-industrial park initiatives in the USA and the Netherlands: first lessons. *Journal of Cleaner Production* 12, pp. 985–995.

Jacobsen, N. (2003). The industrial symbiosis in Kalundborg, Denmark: an approach to cleaner industrial production. In: Cohen-Rosenthal, E. and Musnikow, J. (eds) *Eco-industrial strategies: unleashing synergy between economic development and the environment*. Sheffield, UK: Greenleaf, pp. 270–275.

Korhonen, J. (2001). Co-production of heat and power: an anchor tenant of a regional industrial ecosystem. *Journal of Cleaner Production* 9, pp. 509–517.

——. (2002). Two paths to industrial ecology: applying the product-based and geographical-based approaches. *Journal of Environmental Planning and Management* 45, pp. 39–57.

——. (2004a). Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *Journal of Cleaner Production* 12, pp. 809–823.

——. (2004b). Theory of industrial ecology. *Progress in Industrial Ecology* 1 (1/2/3), pp. 61–88.

Korhonen, J., et al. (2004). Management and policy aspects of industrial ecology: an emerging research agenda. *Business Strategy and the Environment* 13, pp. 289–305.

Lovins, A. B., Lovins, L. H., and Hawken, P. (1999). A road map for natural capitalism. *Harvard Business Review* 77 (3), pp. 145–158.

Lowe, E. A. (2002). *Introduction to eco-industrial parks and networks*. [online]. Retrieved on 8 August 2003 from http://www.indigodev.com

——. (2003). Eco-industrial development in Asian developing countries. In: Cohen-Rosenthal, E. and Musnikow, J. (eds) *Eco-industrial strategies: unleashing synergy between economic development and the environment*. Sheffield, UK: Greenleaf, pp. 341–352.

Lowe, E. A., and Warren, J. (1996). *The source of value: an executive briefing and sourcebook on industrial ecology*. Richland, WA: Battelle Pacific Northwest Library.

Martin, S. A., et al. (1998). Applying industrial ecology to industrial parks: an economic and environmental analysis. *Economic Development Quarterly* 12 (3), pp. 218–237.

McManus, P. (2005). *Vortex cities to sustainable cities: Australia's urban challenge*. Sydney, Australia: UNSW Press.

McManus, P., and Gibbs, D. (2008). Industrial ecosystems? The use of tropes in the industrial ecology and eco-industrial park literature. *Progress in Human Geography* 32, pp. 1–16.

Mirata, M. (2004). Experiences from early stages of a national industrial symbiosis programme in the UK: determinants and coordination challenges. *Journal of Cleaner Production* 12, pp. 967–983.

Mol, A. (2002). Ecological modernisation and the global economy. *Global Environmental Politics* 2 (2), pp. 92–115.

North, J., and Giannini-Spohn, S. (1999). Strategies for financing eco-industrial parks. *Economic Development Commentary* 23 (3), pp. 5–13.

O'Connor, J. (1998). *Natural causes: essays in ecological Marxism*. New York: Guilford Press.

O'Rourke, D., Connelly, L., and Koshland, C. P. (1996). Industrial ecology: a critical review. *International Journal of Environment and Pollution* 6 (2/3), pp. 89–112.

Oh, D.-S., Kim, K.-B., and Jeong, S.-Y. (2005). Eco-industrial park design: a Daedeok Technovalley case study. *Habitat International* 29, pp. 269–284.

Organisation for Economic Cooperation and Development. (1998). *Eco-efficiency*. Paris, France: OECD.

President's Council for Sustainable Development. (1997). *Eco-industrial park workshop proceedings.* October 17–18, 1996, Cape Charles, Virginia. [online]. Retrieved on 5 October 2002 from http://clinton2.nara.gov/PCSD/Publications/Eco_Workshop.html

Randles, S. (2007). Multiscalar landscapes and industrial ecology. *Progress in Industrial Ecology* 4 (3/4), pp. 164–183.

Richards, D. J., Allenby, B. R., and Frosch (1994). The greening of industrial ecosystems. In: Allenby, B. R. and Richards, D. J. (eds) *The greening of industrial ecosystems.* Washington, DC: National Academy Press, pp. 1–19.

Schlarb, M. (2001). *Eco-industrial development: a strategy for building sustainable communities.* Washington, DC: US Economic Development Administration.

Sterr, T., and Ott, T. (2004). The industrial region as a promising unit for eco-industrial development – reflections, practical experience and establishment of innovative instruments to support industrial ecology. *Journal of Cleaner Production* 12, pp. 947–965.

Tibbs, H. B. C. (1992). Industrial ecology: an environmental agenda for industry. *Whole Earth Review* 77, pp. 4–19.

Tudor, T., Adam, E., and Bates, M. (2007). Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): a literature review. *Ecological Economics* 61, pp. 199–207.

Wallner, H. P. (1999). Towards sustainable development of industry: networking, complexity and eco-clusters. *Journal of Cleaner Production* 7, pp. 49–58.

Wasserman, S. E. (2001). *Sustainable development: the case of implementing sustainable development.* Unpublished Master's Thesis, Department of Urban Studies and Planning, Massachusetts Institute of Technology.