LOOKING FORWARD, PUSHING BACK AND PEERING SIDEWAYS: ANALYZING THE SUSTAINABILITY OF INDUSTRIAL SYMBIOSIS

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This paper compares and contrasts two different forms of interorganizational relationships that deal with the production and movement of waste: industrial symbiosis and supply chains. Industrial symbiosis reuses, recycles and reprocesses byproducts and intermediates within the system of organizations, whereas conventional supply chains reduce waste within manufacturing processes and reuse end-of-life products. Although both these models address waste, there is surprisingly little consideration of industrial symbiosis within supply chain research. Yet, industrial symbiosis has much to offer the study of sustainable development within supply chains. Industrial symbiosis emphasizes community, cooperation and coordination among firms, which serves to protect the environmental integrity, social equity and economic prosperity of the region — all hallmarks of sustainable development. However, such tight integration among a diverse set of organizations is difficult to jump start and difficult to maintain. In this paper, we also outline the challenges and offer some ideas on how to address these challenges. We ground our insights from interviews with firms in the Sarnia-Lambton region of Ontario, Canada. This region is home to over 130,000 people, and has a strong physical infrastructure and social structures that have facilitated symbiotic relationships among local businesses.

Keywords: *supply chain management; sustainability; social responsibility; environmental issues*

INTRODUCTION

> *Waste is "raw material in the wrong place"*(Boons 2008, p. 149 — citing Talbot 1919 *Millions From Waste*)

Garbage has earned a bad reputation and with good reason. Waste costs Americans billions of dollars annually in disposal and clean-up costs (Standard and Poor's 2009).[1] Managers have invested considerably in reducing waste within industrial supply chains through total quality management (Corbett and Klassen 2006), as well as reducing pollution by greening their supply chains (Handfield, Walton, Seegers and Melnyk 1997), pollution control (Klassen and Whybark 1999) and pollution prevention (Vachon and Klassen 2006).

The field of industrial symbiosis also addresses waste that moves between organizations. Industrial symbiosis involves the use of one firm's residual resources and byproducts as feedstock for another (Chertow 2000). It applies the well-worn cliché: one man's waste is another man's treasure. Wastes such as fly ash, waste water, steam, heat, sulfur and carbon dioxide (CO_2), for example, have formed the foundation of profitable resource exchanges. In effect, firms create value from their waste products by forming creative interorganizational relationships.

Many such interorganizational arrangements have emerged globally. Regional and colocated organizational networks sharing residual resources have been identified in Kalundborg, Denmark (Ehrenfeld and Gertler 1997),

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[1] The U.S. municipal solid waste industry alone generates more than US$50 billion in revenues, of which between 35 percent and 45 percent is estimated to come from commercial sources.

Kwinana, Australia (van Beers, Corder, Bossilkov and van Berkel 2007), Sarnia, Canada (Venta and Nisbet 1997), Nova Scotia, Canada (Cote and Hall 1995), Rotterdam, Netherlands (Baas and Boons 2004), Queensland, Australia (Roberts 2004), Styria, Austria (Schwarz and Steininger 1997) and throughout the United States (Heeres, Vermeulen and de Walle 2004).

Although research in both supply chains and industrial symbiosis both aim to reduce waste between organizations, surprisingly little industrial symbiosis research has penetrated the research stream on supply chains. Yet, research in industrial symbiosis could help inform an understanding of sustainable development in supply chains.

Whereas the emphasis in supply chain research is waste reduction within a firm, the emphasis in industrial symbiosis is waste reduction over the entire system of firms. In this paper, we argue that this focus on the system of firms facilitates sustainable development. Industrial symbiosis not only reduces pollution, but the tight network of interorganizational relationships fosters social equity and economic prosperity — all hallmarks of sustainable development. As noted in the Call for Papers for this Special Topic Forum, there is much more emphasis in the supply chain literature on the environmental and economic dimensions of sustainable development than on the social equity dimension. A deeper understanding of industrial symbiosis can help inform sustainable development in the context of supply chains.

In this paper, we compare and contrast these two types of interorganizational relationships and illustrate how industrial symbiosis supports sustainable development. Although this manuscript is primarily conceptual in nature, the ideas have been informed by exploratory interviews with members of companies and nongovernment organizations in the Sarnia-Lambton region of Southwestern Ontario in Canada. This region is home to over 130,000 people and was established in the late 1800s to exploit local oil fields. Although there are few remaining fossil fuel resources, the petrochemical firms and their physical infrastructure still form the economic backbone of the region. Local firms now refine imported oil into gasoline, polymers, carbon black, rubbers, fertilizers and ethylene. The region has a strong community, with established industrial and regional nongovernmental organizations, furthering interfirm collaboration in terms of education, safety, environment and health.

This paper proceeds in four parts. In the first section, we review the more conventional views of supply chains, describing forward flows of products toward end users and the reverse flow of end-of-life products back into the supply chain for remanufacturing. We then introduce industrial symbiosis, and suggest that residual wastes create a "sideways" flow of products. In the third section, we discuss the implications of industrial symbiosis for sustainability. In the final section, we identify challenges associated with industrial symbiosis and offer insights into how these challenges can be overcome.

SUPPLY CHAINS: LOOKING FORWARD AND PUSHING BACKWARD

The conventional view of supply chains depicts them as linear flows of physical goods, information and funds between firms and the end users of products (Mentzer, DeWitt, Keebler, Min, Nix, Smith and Zacharia 2001). Physical goods flow downstream, funds flow upstream and critical information on inventory and forecasts flow both ways (Harrison, Lee and Neale 2003). Supply chains involve multiple suppliers and multiple customers, yet because firms focus on a subset of strategically important suppliers and products, supply chains are often conceptualized with a linear orientation (Tan 2002; Rungtusanatham, Salvador, Forza and Choi 2003).

Supply chain researchers recognize the importance of cooperation and integration among supply chain partners. Both broader integration of upstream suppliers and downstream customers through information exchanges (Frohlich and Westbrook 2001), and smoother integration through faster cycle times and smaller batches (Cachon and Fisher 2000; Steckel, Gupta and Banerji 2004), have been shown to generate significant value for supply chain partners. Failing to cooperate could result in a bullwhip effect — small changes in customer demand can be amplified, resulting in large and costly fluctuations in orders (Lee, Padmanabhan, and Whang 1997).

This integration results in supply chains taking on the appearance of a virtual organization (Dyer and Singh 1998; Lambert and Cooper 2000). They are the modern form of a central organizing unit (Miles and Snow 2007), and generate a sense of identity and solidarity. Firms not only compete directly with other firms, but also cooperate with other members of their supply chain to compete against other supply chains (Ketchen and Hult 2007).

Throughout the supply chain, firms simultaneously generate waste and pollution that can compromise profits and harm the natural environment. Supply chain researchers have focused their primary attention in emphasizing manufacturing and management processes within single firms. Firms can control pollution through end-of-pipe remediation and environmental management systems, such as ISO 14001.

A more recent stream of research is also considering the disposal of the end-of-life products. Products at their end-of-life stage have little value to the end consumer; yet there remains residual value in the waste, which has motivated researchers to investigate reverse supply chains (Guide and van Wassenhove 2001). Reverse supply chains reuse, recycle and remanufacture end-of-life products for inclusion in forward supply chains (Kocabasoglu, Prahinski, and Klassen 2007). This practice closes the supply chain loop. In these reverse supply chains, upstream manufacturers become the downstream customers. For example, single-use cameras are remanufactured into new cameras when customers return their film for processing (Savaskan, Bhattacharya, and van Wassenhove 2004). The photo developing lab, therefore, becomes the supplier of the raw material, which flows back to the manufacturer.

Supply chain research, however, has not fully won the battle on waste. Waste is created in each step of the supply chain. Further, the waste contains considerable residual value, such as CO_2 emissions, spent solvents, off-specification products, chemical intermediates and unused scrap materials. Further, reverse supply chains depend on a sufficient and sustained supply of end-of-life products to justify the costly investments reverse supply chains require (Geyer, van Wassenhove, and Atasu 2007). In the next section, we show how industrial symbiosis addresses this waste and captures residual value.

INDUSTRIAL SYMBIOSIS: PEERING SIDEWAYS

Defining Industrial Symbiosis

Industrial symbiosis occurs when a firm's manufacturing waste forms the feedstock for another firm (Frosch and Gallopoulos 1989). Waste, such as low-grade heat energy, water and byproducts, can lead to collaborative opportunities between otherwise independent organizations (Chertow 2000). The supply manager provides a "sink" for the supplier's waste, productively using byproducts and chemical intermediates.

Industrial symbiosis is designed on a natural ecosystems metaphor in which two dissimilar organisms mutually benefit from a relationship (Chertow 2000; Ehrenfeld 2004). The implementation of this ecological metaphor has taken many forms. Industrial symbiosis has been studied in regional industrial symbiosis networks (Baas and Boons 2004; Mirata 2004; Ashton 2008; Howard-Grenville and Paquin 2009), eco-industrial parks (Cote and Hall 1995; Roberts 2004; Jacobsen 2006) and even within a single business group (Zhu and Cote 2004). It covers cases in sugar production (Zhu and Cote 2004), pharmaceuticals (Ashton 2008), harbors (Baas and Boons 2004), pulp and paper (Korhonen 2002) and heavy industrial sites (Ehrenfeld and Gertler 1997; Jacobsen 2006).

The industrial park at Kalundborg, Denmark, is the most cited exemplar of industrial symbiosis. This park is anchored by four major industrial players: the Asnaes power station, a Statoil oil refinery, a Novo Nordisk's pharmaceutical plant and Gyproc, a wallboard manufacturer. Their wastes, including heat, water, flue gas, steam, fly ash and scrubber sludge, have spawned a variety of waste reuse and remanufacturing relationships over the course of 35 years. In one process, sulfur dioxide is removed from flue gas yielding gypsum that then supplies a wallboard manufacturer. In another, nickel and vanadium are reclaimed from fly ash for use in the manufacture of cement. In yet another example, wastewater is cascaded between multiple partners, cutting water consumption by 25 percent (Ehrenfeld and Gertler 1997). In total, over 11 exchanges are evident in this industrial community.

In contrast to Kalundborg's tightly knit network of symbiotic relationships among industrial partners, Sarnia-Lambton is dotted with pockets of symbiotic activity. We outline four such symbiotic relationships in Table I and discuss each in turn.

The first example is Terra Industries. Figure 1 illustrates both Terra's conventional supply chain and industrial symbiosis activities. Terra Industries draws raw materials, including natural gas, power, air and water, from the natural environment and from suppliers. Terra transforms those resources into a variety of nitrogen-based fertilizers, including granulated urea and urea and ammonia nitrate solution in various concentrations. Through this process, Terra generates three streams of valuable byproducts: steam, CO_2 and ammonia. The first byproduct stream is comprised of CO_2 emissions and residual heat. Both streams are low grade; the CO_2 is blended with air and thus costly to reclaim, and the steam is not hot enough to drive a turbine. However, an innovative arrangement with Enviro-Fresh, a greenhouse operator, has put both of these streams to productive use; the residual steam heats the greenhouse and the CO_2 increases crop yields. In addition to low-grade CO_2, Terra also generates pure CO_2 as a byproduct that it pipes to Air Liquide, a gas specialist. Air Liquide sells the CO_2 to beverage manufacturers, which use the gas in soft drinks and fizzy water. Finally, as a result of a mismatch between its production and upgrading plants, Terra produces more ammonia than it can upgrade. Terra, together with Ontario Power Generation, has found that ammonia's high hydrogen content makes it ideal as a reagent that reduces nitrogen oxide emissions when sprayed into a power plant's exhaust stream.

The second example is offered by the Cabot Canada, which purchases residual oil feedstock from local oil refineries to produce carbon black. Cabot's carbon black has been used in a myriad of products from tires and plastics to coatings and pigments. Residual oil products that do not meet the quality standards set by Cabot are combusted by other refinery customers to generate electricity and fuel ships, thereby making productive use of residual oil product.

A third pocket of industrial symbiosis occurs at LANXESS, a large manufacturer of rubber polymers and other chemical intermediates. The bulk of LANXESS' feedstocks are co-products from a cracked crude hydrocarbon mixture from which the lighter ethylene and propylene products have been removed by distillation. LANXESS takes the crude C-4 mixture and distills off the butadiene, which is sold to other companies as a

TABLE I

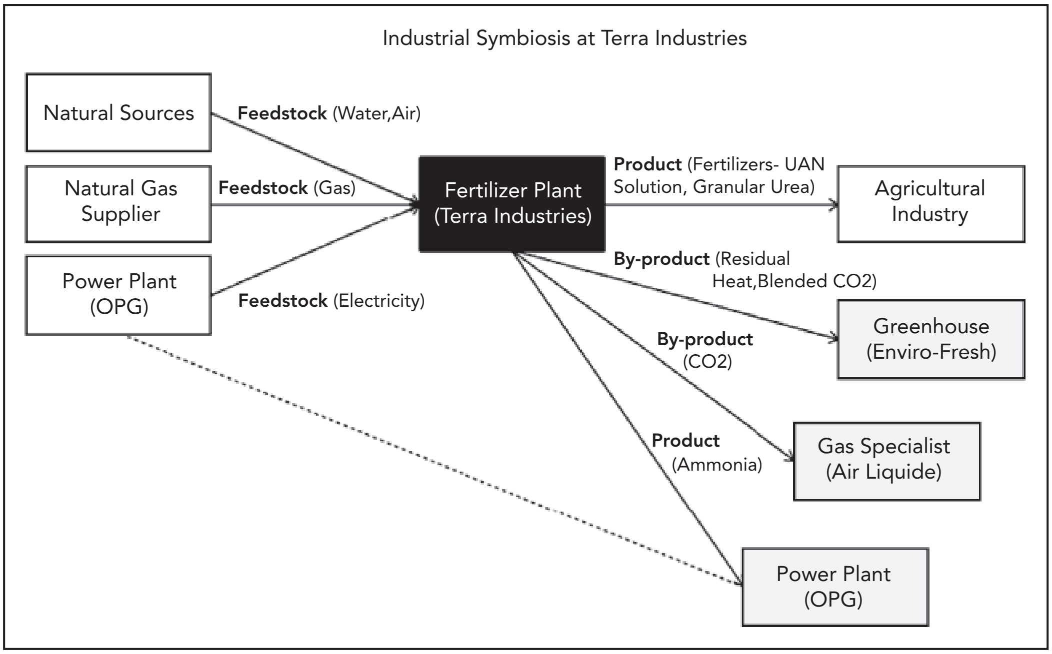
Industrial Symbiotic Relationships in Sarnia Lambton

Company	Description	Nature of Exchange	Byproduct Flow
Terra Industries	Small North American fertilizer company with 1,000 employees; 150 employees at the Sarnia-Lambton plant	Sells low-grade heat and CO_2 for use by Enviro-Fresh, a colocated greenhouse operation	Low-grade heat and CO_2
		Sells CO_2 to Air Liquide for use in soda drinks	CO_2
		Sells excess ammonia solution to power plants in order to reduce nitrogen oxide pollution	Ammonia solution
Cabot Canada	Medium-sized international fine-particle manufacturer based in North America with 4,500 employees	Buys residual oil feedstock from a local oil refinery and uses this for the production of carbon black	Residual oil feedstock
		Plans to reduce land filling of carbon products by increasing sales to facilities that convert product to other forms of energy	Carbon black
LANXESS	Specialty chemical company with sales of EUR 6.58 billion in 2008 and 14,600 employees in 23 countries. The company is represented at 44 production sites worldwide. The core business of LANXESS is the development, manufacturing, and marketing of plastics, rubber, intermediates and specialty chemicals.	Chemical Butadiene is an intermediate that can be used to produce plastics and vinyls	Butadiene
		Receives their core crude oil feedstock, which is a co-product from a local upstream natural gas cracking facility	Crude oil mixture
Suncor Energy Inc.	Integrated energy company. Suncor's operations include oil sands development and upgrading, conventional and offshore oil and gas production, petroleum refining, and product marketing. The Sarnia-Lambton ethanol plant has 50 employees.	Captures and sells CO_2 for use in soda drinks	CO_2
		Sells dried distiller grains (DDGs) to cattle farmers for feed	DDG

chemical intermediate for the production of a variety of rubber polymers or plastics. The remainder of the crude C-4 stream is then run through an isomerization process to produce isobutylene, which LANXESS then uses as a feedstock to manufacture butyl rubber. The balance of the crude is sold as raffinates, which are used as gasoline octane enhancers in the petroleum fuel industry.

Finally, Suncor produces ethanol from corn, and generates CO_2 and distiller grains in the process. The company captures its CO_2 for Praxair, a provider of industrial gases, for use in the production of soft drinks. Suncor also dries and ships the distiller grains to farms across Southern Ontario where they are fed to cattle. Through this process, Suncor is able to extract their product, ethanol, from the corn, without disrupting its end use in

FIGURE 1
Industrial Symbiosis at Terra Industries



agriculture. In doing so, Suncor counters some of the criticisms in the food versus fuel debate that has circled the issue of using corn for ethanol.

These examples provide a general sense of industrial symbiosis in action. Next, we compare and contrast industrial symbiosis with forward and reverse supply chains, drawing on these examples to illustrate the differences.

Contrasting Conventional Supply Chains with Industrial Symbiosis

Industrial symbiosis and conventional supply chains are both representations of interorganizational relationships based on product flows, but they differ markedly. Although both models recognize the importance of integration and coordination, industrial symbiosis involves a much tighter network of diverse relationships. In Table II we summarize the key differences between industrial symbiosis and conventional supply chains, both at the level of the supply chain system and the level of the individual firm within that system, and describe them in greater detail below.

A key difference between industrial symbiosis and conventional supply chains is reflected in the coordination mechanisms between firms. Industrial symbiosis emphasizes community, cooperation and connectedness (Ehrenfeld 2000). Symbiotic partners are part of a community that provides a myriad of different mechanisms to connect partners (including trade and volunteer associations, and social clubs), and nurture idiosyncratic, mutually beneficial relationships among employees. Thus, organizational members of symbiotic partners have vested interests in preserving the symbiotic partnerships that extend beyond economic transactions. Suncor's sustainability vision, for example, supports the local farming community. As a result, the company returns the spent dried distiller grains after the ethanol is extracted to farmers to feed cattle. Suncor extracts value from the supply chain, but does not disrupt it. Typical ethanol producers, on the other hand, use the spent grains to cogenerate electricity, consuming the feed for their own uses.

Conventional supply chains are coordinated through information exchanges, such as orders, forecasts, marketing and inventory information. Consequently, members of forward and reverse supply chains fall victim to competitive tactics as each vies for power in the chain. Partners involved in industrial symbiosis, however, are more likely to uncover innovative and mutually beneficial responses to external threats because of the rich information exchanges that come with personal relationships.

As a consequence of this high level of coordination, many of the relationships formed in industrial symbiosis arise out of serendipity and are somewhat idiosyncratic to the partners. These organizations capitalize on the unique opportunities afforded by geographic proximity, excess resources and potentially useful wastes. Colocation is often important for industrial symbiosis because many waste products have short shelf lives, have hazardous properties, are difficult to transport (bulky or toxic) or have such low value that they do not warrant the expense of transporting

TABLE II

Contrasting Industrial Symbiosis with Conventional Supply Chain Approaches

	Industrial Symbiosis	Forward and Reverse Supply Chains
System level		
Coordination	Based on norms of community and cooperation	Often dominated by a large, powerful firm, and/or competitive market mechanisms
Idiosyncratic relationship	Supply chain relationships take advantage of unique fit between firms — i.e., geographic proximity	Supply chain relationships designed based on need — i.e., buys and sells globally
Firm and flow heterogeneity	Cooperating firms are diverse and drawn from multiple industries	Cooperating firms focus on delivering a single type of product
Structure	A dense network structure, with interconnecting ties in many directions	Generally, a linear structure with multiple suppliers and multiple customers
Firm level		
Product identity	Products produced are independent of a firm's identity	Products produced are consistent with a firm's identity
Product manufacturing	Multiple products produced from a set of inputs — sold to multiple industries	Single product produced from a set of inputs — sold to a single industry
Strategic logic	Firms sell products that they have — seeking a higher value use of waste, byproducts and chemical intermediaries. Effectuation logic	Firms design and sell products to meet customer needs. Causation logic
Perception of waste	Waste is seen as feedstock for other production processes	Waste is to be minimized

(such as CO_2). Terra Industries, for example, is able to pipe its ammonia solution to nearby Ontario Power Generation, rather than incurring the costs and complexity of granulating the solution in order to transport it further, as would be required of competitors. Conventional supply chains, in contrast, are rarely confined by geography, commonly sourcing raw materials from the least expensive global supplier and selling products internationally (Roth, Tsay, Pullman and Gray 2008).

These opportunistic relationships yield considerable heterogeneity in terms of organizational characteristics and material flows in symbiotic relationships. Large organizations may partner with small ones because of the small volumes of byproducts. Heavy industry firms may partner with more service-oriented firms. For example, Terra Industries was a large chemical fertilizer plant that produced residual heat and CO_2. Enviro-Fresh, a greenhouse operator growing bell peppers, was founded primarily to benefit from these residual products. Conventional supply chains rarely establish these unique waste reuse relationships and thus manage a more homogeneous set of customers and customer relationships.

This high level of coordination and colocation among relatively heterogeneous organizations in industrial symbiosis results in quite a different network structure than for conventional supply chains. Industrial symbiosis results in a dense web of relationships. One firm's customer can also be its supplier or that of its other customers. Consider Terra Industries, which sells nitrogen-based fertilizers to the agricultural industry, and ammonia solutions to the power industry, CO_2 for a variety of manufacturing purposes and excess heat and steam to a colocated greenhouse operator. Terra's residuals are sold to numerous firms in a variety of industries. The Ontario Power Generation not only supplies Terra electricity, it also uses the ammonia that Terra produces. These relationships result in a branched interorganizational structure that more closely resembles a web than a chain. In contrast, conventional approaches to supply chains focus on forward or backward flows of products that are sold into a relatively homogeneous market. Before establishing interorganizational relationships to sell residual urea solution, heat and CO_2, Terra's business only served the agricultural industry. Although a network structure exists in both industrial symbiosis and conventional supply chains, the networks are tighter and denser in industrial symbiosis.

In addition to these system-level differences, there exist firm-level differences between symbiotic and conventional approaches to supply chains. Firms engaging in industrial symbiosis identify more strongly with the materials and resources they process, whereas firms in a conventional supply chain identify more closely with the end products. For example, the Cabot Canada has found a myriad of uses for its carbon black materials, including in adhesives, tires, batteries, coatings and printing inks. The firm has been identified with carbon black since the material was invented at the end of the 19th century.

This strong identification to inputs usually implies that firms involved in industrial symbiosis are diversified. They aim to extract as much value from inputs as possible. Firms in conventional supply chains, on the other hand, focus on the output or a single product and do not appear as diversified. Figure 1, for example, illustrates that Terra not only sells its main fertilizer product, but also the residual heat, CO_2 and ammonia.

The strategic logic of industrial firms in symbiotic relationships also differs from firms in more conventional supply chains. Symbiotic firms are governed by a logic of effectuation in which opportunities are created, rather than merely discovered (Sarasvathy 2001). This logic implies that symbiotic firms seek markets based on available manufacturing waste, rather than design and manufacture products to the exacting needs of customers. Firms involved in industrial symbiosis aim to *extract* value from the raw materials, hoping to find new uses for unused materials. This logic characterizes Terra Industries' search for synergies not only with their symbiotic partners, but more broadly within the petrochemical industry in the region, which are not always immediately apparent. Terra, for example, actively searched for an entrepreneur who could build greenhouses on their land, because there was no obvious business that could use the residual heat and CO_2. However, firms in conventional supply chains allow customers to define their needs and work backward to design the product.

Collectively, these factors mean firms involved in industrial symbiosis look for the potential value that lies in a resource. Firms minimize waste by extracting value from the entire resource. At LANXESS this potential value is so firmly ingrained that all of the crude C-4s are refined and either sold or used productively thereby eliminating wastes. Chemicals like butadiene, which cannot be used in the manufacture of LANXESS' products, are sold as a chemical intermediate. Consequently, waste is minimized for the system of organizations, even though it may not be minimized for a single organization. Firms in conventional supply chains, on the other hand, see the risks or costs in their waste products and thus aim to reduce waste within each organization.

Typically, each member of a conventional supply chain aims to minimize waste. Without waste or byproducts, however, the rich relationships that comprise industrial symbiosis cannot occur (Oldenburg and Geiser 1997; Chertow 2000). Pollution prevention by individual firms in a supply chain can be counterproductive to industrial symbiosis, since manufacturing waste may be below reusable levels (Oldenburg and Geiser 1997; Chertow 2000). Government regulations that prohibit or limit handling or transporting waste, as in the case of conventional supply chains, can also inhibit industrial symbiosis (Oldenburg and Geiser 1997). In the next section we illustrate that the focus on the system of firms in industrial symbiosis offers the added benefit of supporting social equity and economic prosperity, and forms the foundation of sustainable development.

THE SUSTAINABILITY OF INDUSTRIAL SYMBIOSIS

Sustainable Development

The World Commission on Environment and Development defined sustainable development in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 43). Three principles or pillars have emerged to guide sustainability research and practice: environmental integrity, social equity and economic prosperity (Elkington 1998). Environmental integrity guards against excessive consumption and resource depletion in order to maintain the capacity of the earth's ecosystems to provide for human needs. Social equity ensures that all people, including underprivileged people and future generations, are afforded equal opportunities. Economic prosperity acknowledges that in order to provide a reasonable quality of life, goods and services need to be produced and distributed effectively and efficiently (Bansal 2005).

These three pillars are interconnected. Economic prosperity can be secured by privileging the needs of a small group over the broader society's needs, but this undermines social equity. Economic prosperity can also compromise environmental integrity by quickly consuming natural resources in order to generate higher short-term profits. However, it is possible to construct win-win-win practices that support all three pillars.

The supply chain literature has focused most of its attention on the environmental dimensions of this definition. The emphasis has been on the reduction of wastes through pollution control and pollution prevention. Pollution control captures, controls and treats pollution at the end of the pipe (Vachon and Klassen 2007): firms aim to clean up the mess created by manufacturing processes. Pollution prevention, on the other hand, tackles pollution at the source, before it is created, through product and process redesign (Klassen and Whybark 1999). In each of these cases, waste is treated as pollution, something to be avoided or eliminated. More recently, some supply chain researchers have acknowledged the residual value associated with waste (Linton, Klassen and Jayaraman 2007).

Industrial symbiosis is important for sustainability, not only because of how wastes are handled, but also because it addresses the social and economic aspects of sustainability. In fact, industrial symbiosis has been hailed as the "Science of Sustainability" (Allenby 1999). In part this is because the ecosystem upon which industrial symbiosis is modeled is considered sustainable (Korhonen 2001). Some scholars go even further, touting industrial symbiosis as the model that advances the sustainability paradigm (Ehrenfeld 2000). Industrial symbiosis produces environmental integrity, social equity and economic prosperity simultaneously.

Industrial symbiosis maintains *environmental integrity* by minimizing the industrial system's ecological footprint through three mechanisms: the productive use of waste, high resource intensity and accelerated biological degrading processes.

Waste is low because industrial symbiosis captures residual flows, thereby emitting little waste and imposing little strain on nature's "sinks" (Huber 2000). Sinks are nature's mechanism for absorbing high concentrations of materials from discarded consumer products, manufacturing pollution and even CO_2 and residual heat (Sterman 2002). For example, Terra Industries redirects significant amounts of CO_2 and low-grade waste heat from the atmosphere to Enviro-Fresh, a colocated greenhouse. The vegetables effectively sequester CO_2, reducing carbon emissions that contribute to climate change, while simultaneously increasing the greenhouse's efficiency. This relationship also reduces the amount of energy Enviro-Fresh draws from the grid.

Similarly, industrial symbiosis increases resource intensity, enabling partner firms to extract greater value from existing resources. Intensity is increased as partner firms replace virgin resource streams with residual waste streams. Firms engaged in industrial symbiosis extract fewer resources from and emit less waste to the natural environment. Therefore, nature's resources are reused multiple times before disposal. Suncor, for example, captures its own CO_2 and sells the gas to Praxair for compression into dry ice and use in soft drinks.

Finally, industrial symbiosis accelerates the biological degradation of waste, which decreases the concentrations and toxicity of the emissions in natural systems. Industrial partners in symbiotic relationships simulate the role of natural scavengers, which decompose dead vegetation or animals, returning nutrients to the earth. For example, Cabot Canada breaks down residual oil feedstock into carbon black and a variety of gases including nitrogen oxide, carbon monoxide and CO_2. Although these gases may have an impact on natural systems, they are less harmful than residual oil feedstock.

Industrial symbiosis also enhances the *social equity* within communities. As we argued earlier, industrial symbiosis fosters strong social and professional relationships between members of the business community, like those developed in the Sarnia-Lambton region. Industrial symbiosis encourages a shared sense of community that engenders a collaborative, positive response to adversity. Firms in symbiotic relationships embed themselves in the local community, fostering a more responsible orientation (Granovetter 1985). While conventional supply chains typically transact with only two types of actors (suppliers and customers), firms involved in industrial symbiosis engage in many different types of relationships, forming a dense network of interdependent firms. Partners come to rely on each other, investing in capital-intensive, relationship-specific assets, such as pipelines and CO_2 capture technologies. As a result, under adversity, partners are more likely to solve problems collaboratively and innovatively, since it is in the collective interest to sustain the relationship.

Further, economic wealth generated from local natural resources is retained within the local community, which is in sharp contrast to global supply chains where the lenders, employees and consumers are geographically removed (Roth et al. 2008). Firms involved in industrial symbiosis capture economic rents from local industrial activity, and the rents ultimately flow to the communities that steward those natural resources. This stewardship has a direct and positive effect on the firms reducing the pollution, which in turn enhances social equity through decreased risk to human health from toxic emissions. In fact, the Sarnia-Lambton region is starting to shake off its long-held moniker of "chemical valley" from the petrochemical days, in no small part due to the symbiotic activities in the region. The toxins and waste products entering the local air, water and land have been dramatically reduced.

Industrial symbiosis also helps to build *economic prosperity*. Firms generate revenues from resources that would otherwise be discarded, such as the revenue generated by the oil refinery that sold its residual oil as feedstock to Cabot Canada. Further, waste disposal and clean-up costs are mitigated. The volume and toxicity of many wastes — such as residual oil feedstock, off specification carbon black and bulky dried distiller grains — makes them costly to dispose because they require significant remediation, transportation, tipping fees and containment.

In summary, industrial symbiosis supports the three pillars of sustainable development. From the above discussion, we argue that industrial symbiosis is a sustainable approach to economic development, one upon which future generations can rely.

IMPLEMENTING INDUSTRIAL SYMBIOSIS

The Challenges of Implementing Industrial Symbiosis

The high degree of community, cooperation and coordination demanded of industrial symbiosis is hard to achieve. There are both technical and social challenges.

The two major technical challenges pertain to the quantity and appropriate quality of industrial byproducts. The social challenges arise from the need to trust partner firms to meet those quantity needs and quality standards. We discuss each in turn.

Firms must ensure that adequate supply of their byproducts be provided to symbiotic partners. However, the quantity of the byproducts is determined by the demand for the core products. Further, the production processes of many firms require inputs that conform to exacting quality standards. However, because firms focus most of their attention on their core product, the quality of their byproducts can be compromised. Wide quality variance can inhibit the success of many manufacturing processes (Cohen-Rosenthal 2000; Heeres et al. 2004). For example, Terra Industries' residual steam is not hot enough for most uses, and its residual CO_2 is impure because it is blended with air. Enviro-Fresh greenhouses offer one of the few productive uses of these wastes.

Implementing industrial symbiosis also carries social challenges associated with the personal relationships that are at its very core (Cohen-Rosenthal 2000; Hoffman 2003; Seuring 2004; Boons and Howard-Grenville, forthcoming). Industrial symbiosis requires trust and cooperation among its diverse partners (Chertow 2000). Managers must know their respective partners and consider their mutual interests in production decisions that could influence the supply of byproducts used by the industrial symbiosis network. Although, on the one hand, the diverse relationships afford flexibility, on the other, they can also become a liability. The relationships can become embedded, and inhibit adaptation and innovation to externally driven opportunities and challenges. Relationship-specific assets and contracts oblige firms to provide customers and partner firms a prescribed volume of byproducts. Yet, meeting these demands can be challenging.

These restrictions limit the ability of the symbiotic system to respond to shocks. For example, if the demand for fertilizer decreased, Terra Industries could idle a portion of its operations, but this would reduce the quantity of CO_2, steam and ammonia solution produced, which would have a knock-on effect on Air Liquide, Enviro-Fresh and Ontario Power Generation. At the very least, these rigidities impose additional costs, as the recipient firms will have to source inputs from elsewhere. At the worst, the failure of one company could cause reverberations through the system, leading to a collapse of the symbiotic relationships.

Not only must managers monitor their own market, but they must also keep abreast of their supply partners' markets. For example, the managers at Terra Industries were faced with significant challenges in retooling their marketing and sales force in order to sell urea solution to the power generation and diesel engine markets — both markets for which they had little information. Managing these customers, in addition to the agricultural firms to which they were accustomed, raised challenges. Learning about and catering to each new market consumes valuable managerial attention, making it difficult to react quickly to downstream product changes.

OVERCOMING THE CHALLENGES OF IMPLEMENTING INDUSTRIAL SYMBIOSIS

Strong communities among diverse firms and industries are critical to industrial symbiosis. That is why research on industrial symbiosis focuses on industrial parks (Cote and Hall 1995; Chertow 2007). Industrial parks possess the physical infrastructure for sharing materials, as well as social structures for facilitating collaborations. When communities possess a diverse industrial base, a simple meeting can spark the creativity, courage and commitment to initiate a symbiotic relationship. The Sarnia-Lambton region, for example, not only possessed the physical infrastructure (such as pipelines and a dense array of plants that remained from a largely depleted petrochemical industry) that facilitated the transfer of volatile byproducts, but also the social structures (such as professional associations and golf clubs) that facilitated personal relationships.

Equally important is trust among potential partners (Gibbs 2003). Third parties such as government, industry associations and other coordinating organizations can help to build trust. These organizations can facilitate information sharing (Heeres et al 2004), broker relationships (Paquin and Howard-Grenville, forthcoming), champion shared services (van Beers et al. 2007) and serve as anchor organizations (Chertow 2000).

Once trust is established, it is important to share critical processes and data regarding each other's operations. If manufacturing processes are well understood and manufacturing waste readily apparent, less data need to be shared. In addition, information brokers can be particularly useful in performing vital matchmaking services (Mirata 2004).

Industrial symbiosis is more likely when mutually beneficial relationships that align the interests of all parties are formed. For example, a proposal to colocate a greenhouse beside an oil refinery may be more interesting to the oil refinery if the greenhouse produced biofuels that the oil refinery could process and sell. The mutual benefit that results becomes truly symbiotic, and not merely the sinking of one firm's waste into another's production processes.

These technical and social challenges are not insignificant. In fact, we know of no perfect symbiotic system of firms in which all wastes are internalized within the system and completely consumed. Even Kalundborg, the most cited example of industrial symbiosis, still generates wastes through its member firms' production processes. Consequently, most firms do not rely on a pure symbiotic model, but a hybrid form that integrates industrial symbiosis with forward and reverse supply chains. A hybrid model is based on a conventional supply chain, but incorporates elements of industrial symbiosis. The most elementary example of a hybrid supply chain is where the wastes of one firm are used as inputs for another firm's processes, in exchange for money. This rather minimal form of industrial symbiosis helps to contain the level of complexity that comes with interdependence. In fact, hybrid models may be able to achieve many of the benefits associated with industrial symbiosis, without compromising the resiliency associated with the rigidity and inflexibility of industrial symbiosis.

CONCLUSION

In this paper, we explored the sustainability of industrial symbiosis, a specific form of supply chain. We did this first by contrasting how industrial symbiosis differs from a more conventional view of supply chains. We argued that industrial symbiosis offers a model of sustainable development because of its emphasis on system-level waste reduction opportunities. Such a perspective demands tight integration, coordination and trust among partners, which in turn serves to build environmental integrity, social equity and economic prosperity within the region. We also identified some of the challenges associated with industrial symbiosis and offered some suggestions on how these challenges might be overcome. Our insights were drawn from an analysis of symbiotic activities in the Sarnia-Lambton region of Ontario, Canada.

This analysis makes an important contribution to the supply chain literature by clearly articulating the differences between the two different types of interorganizational relationships. Within conventional supply chains, new products move forward and end-of-life products move in reverse, whereas within industrial symbiosis, partnerships are created from the flow of byproducts. Industrial symbiosis has had little influence in the supply chain literature to date and yet there is considerable opportunity to learn about the nature of these relationships. Industrial symbiosis offers an opportunity to extend beyond pollution control and pollution prevention, and recognize the economic, social and environmental value in using waste within a system of organizations. It demonstrates the importance of considering the whole system of organizations in assessing sustainability (Choi, Dooley and Rungtusanatham 2001).

Globalization has been extending the reach of supply chains, so that producers and consumers are becoming ever more distant (Roth et al. 2008). Alongside is the push for standardization to further enable firms to work together. Both of these trends are in sharp contrast to the geographical colocation and diversity demanded by industrial symbiosis. If sustainable development is to be a business mandate, then it is incumbent on businesses to recognize the importance and relevance of geographical proximity and diversity (Heeres et al 2004; Roberts 2004; Gibbs and Deutz 2007).

In this paper, we also sounded a cautionary note. Industrial symbiosis is a challenging undertaking. Managers must recognize that industrial symbiosis heightens the degree of interdependence and complexity between partner firms, which increases the level of risk, if not managed carefully. Firms must manage these types of interdependences, establishing coordinating mechanisms that help the system absorb exogenous and endogenous shocks.

This research points to the economic, environmental and social opportunities created by waste. It suggests that firms not only add value to resources along a supply chain, but can also extract more value from byproducts, intermediates and other residuals. By looking to industrial symbiosis, supply chain research can facilitate a set of interorganizational partnerships that could lead to greater sustainable development.

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