Report Number 3

The Industrial Symbiosis Research Symposium at Yale: Advancing the Study of Industry and Environment

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Yale Center for Industrial Ecology

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The Industrial Symbiosis Research Symposium at Yale: Advancing the Study of Industry and Environment

Marian Chertow, Weslynne Ashton, and Radha Kuppalli

Abstract

Industrial symbiosis (IS), a sub-field of industrial ecology, is principally concerned with the cooperative management of resource flows through networks of businesses as a means of approaching ecologically sustainable industrial activity. Isolated researchers in a broad range of disciplines have investigated industrial symbiosis from a variety of starting points without a common agenda. The Industrial Symbiosis Research Symposium was held in January 2004 at Yale University, bringing together more than 30 experts from 15 countries to discuss critical questions and issues in this emerging area. The purpose of the Symposium was to give researchers an opportunity to share their knowledge and experience on the state of research, to determine areas of possible cross-fertilization among disciplines, and to establish research priorities. *The Industrial Symbiosis Research Symposium at Yale: Advancing the Study of Industry and Environment* is a report on the first global research conference in this area.

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WITH THANKS

In 1989 Robert Frosch and Nicholas Gallopoulos, writing in *Scientific American*, described an industrial ecosystem in which "the consumption of energy and materials is optimized and the effluents of one process . . . serve as the raw material for another process." This image has stimulated the imaginations of those interested in applying the biological analogy underlying the concept of ecosystems to industrial activities ever since. The 1989 article "Strategies for Manufacturing" is widely considered to be the first article of today's field of industrial ecology. Now industrial ecology in the academic world has at least one journal, a scholarly society with newsletter, many websites and listservs, a biennial research meeting, and a biennial conference. Many have picked up the term and applied it to environmental sustainability questions around the world.

New ideas, of course, never exist in isolation. Those interested in the notion that one company's waste can become another company's feedstock quickly found proponents of such ideas among planners and designers reinventing cities, engineers working in co-generation and wastewater reuse, ecologists pondering stability and diversity, business managers optimizing industrial operations, and community leaders considering economic development and its effects. Various examples were identified of one degree or another of such resource sharing and a new name, industrial symbiosis, was coined by our esteemed colleagues in Kalundborg, Denmark. Coming from industrial ecology, I have written previously that:

> *Industrial symbiosis, as part of the emerging field of industrial ecology, demands resolute attention to the flow of materials and energy through local and regional economies. Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity . . .*[i]

[i] M.R. Chertow (2000). "Industrial Symbiosis: Literature and Taxonomy." *Annual Review of Energy and Environment*, 25: 313-337.

While much work and exploration was done around related concepts such as eco-industrial parks, by-product synergy, and resource productivity, by 2004, what seemed needed was an opportunity to gather together researchers in these areas for a meeting to assess the current state of knowledge in the field and to catalyze further investigation. Organized hastily, based on e-mails during the summer of 2003 to many of those who had published in the field, the first-ever global Industrial Symbiosis Research Symposium was born. In the end, some 34 brave souls from 15 countries turned up on the Yale campus from January 7-9, 2004. This report recounts

the events of the meeting as a summary and record that can be sent out to all those interested in industrial symbiosis research. Our greater goal, beyond this report, is to stimulate more knowledge and understanding of how we can achieve environmental benefits through collective action that is greater than the sum of the individual parts.

The organizational task for me was just to grab hold of the energy and support that was already out there to convene such a meeting and to make sure we could pay for some meals and other expenses we would incur. A number of groups came to our aid and I would like to list them here to acknowledge their generosity in supporting our purpose. This important funding was used to cover the organizational expenses of the Symposium as well as to cover the travel costs of several participants.

- The Yale Center for Industrial Ecology;
- The Henry Luce Foundation concerned with Yale projects in China and southeast Asia;
- The Coca-Cola World Fund of the Yale Center for International and Area Studies;
- The Joel Omura Kurihara Fund named in honor of a Yale F&ES alumnus from the class of 1992 to support activities around business and environmental issues;
- Windmar Associates of San Juan, Puerto Rico, which sponsored the Symposium banquet.

In addition, the following groups supported attendees: The Emil Aaltonen Foundation, the Greening of Industry Network – Asia, and the National Research Center for Environmental and Hazardous Waste Management, Chulalongkorn University, Bangkok, Thailand.

Two people were indefatigable in making sure that the Symposium went forward with a thoughtful agenda and careful organization. Thanks go to Weslynne Ashton, a wise Yale doctoral student who is writing her dissertation about industrial symbiosis, and Michelle Portlock, intrepid former Coordinator of the Center for Industrial Ecology. My Yale colleagues Professor Tom Graedel and *Journal of Industrial Ecology* Editor Reid Lifset were always available for consultation, as were Noel Jacobsen at Rothskilde University in Denmark and John Ehrenfeld, Executive Director of the Center for Industrial Ecology. Many participants made excellent suggestions about content, topics, invitees, and organizational issues which were greatly valued. Radha Kuppalli, even as a first semester masters student, dove right in to help with fundraising and coordination. Woon Kwong Liew figured out how to connect some international participants over the wires. Doctoral students Shi Han and Jeremiah Johnson, as well as Alanya Schofield from Yale College, joined Weslynne and Woon Kwong as key scribes and note takers of the actual meeting from which this document was drawn. Gus Speth, Dean of the Yale School of Forestry and Environmental Studies, supported our effort all the way and inspired us with remarks at our banquet.

Jane Coppock, Editor of the Yale F&ES Publication Series, and new Center for Industrial Ecology Coordinator Gretchen Rings played key roles in editing and formatting this report recounting our rich and warm meeting. Not to be outdone by one of Yale's famous a capella singing groups at the dinner on January 8th, by lunchtime on January 9th the symposium formed itself into its own singing group and, under the soulful leadership of Judy Kincaid, Andy Mangan, and Somporn Kamolsiripichaiporn, rang out these original words (to the tune of "With a Little Help from My Friends"):

What would I do if I had lots of waste?
Would you stand up and walk out on me?
You've got some cash and could buy up my trash
For reuse at your plant, don't you see.

"With a little help from my friends . . ."

Let me offer my thanks, in prose in lieu of song, to all who made the Symposium possible.

Marian Chertow, Ph.D., Symposium Chair
Yale School of Forestry and Environmental Studies

INTRODUCTION

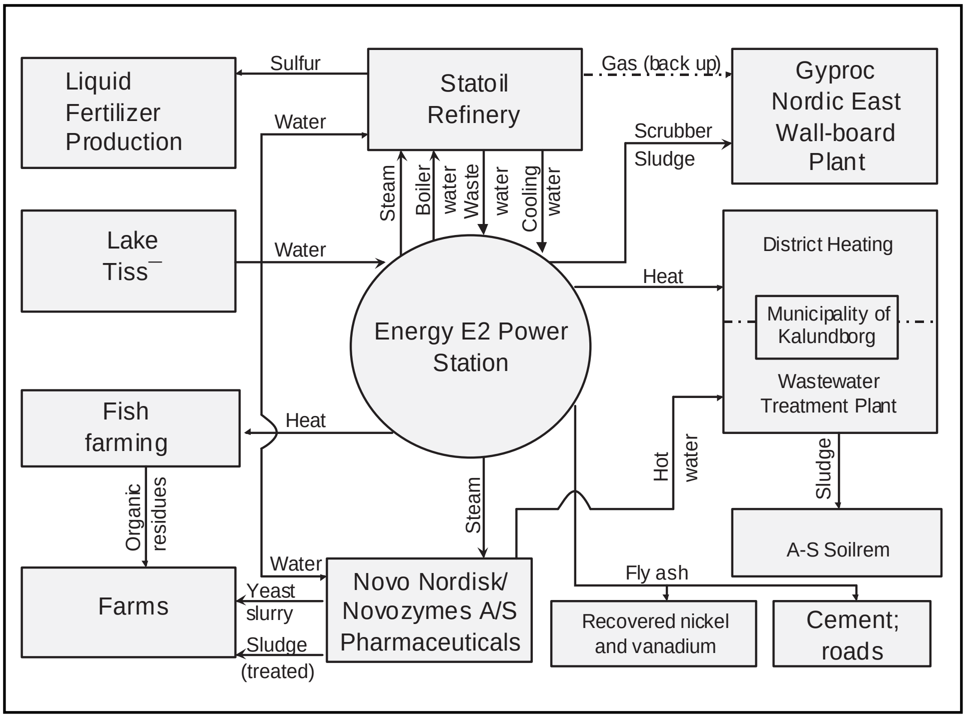
Industrial ecology has emerged in recent years as a new multi-disciplinary field at the nexus of environmental science, engineering, business, and policy. Its challenge is to consider industrial systems within the context of the natural systems they occupy. The field is engaged in studying environmental aspects of the technological society from a systems perspective.

Within industrial ecology, the sub-field of "industrial symbiosis" takes as its starting point a vision of industry organized along the model of an ecosystem. In this way it draws on the concept of biological symbiotic relationships in which unrelated organisms find mutual benefit through the exchange of resources, typically wastes. The term "industrial symbiosis" first appeared in the economic geography literature in the 1940s to describe "organic relationships" between dissimilar industries, including the use of waste products from one as input to another.[ii] There are numerous historical examples of such symbioses, through which a myriad of commercial uses were developed to eliminate waste.[iii] Modern-day industrial symbiosis looks to the environmental, as well as economic, consequences, of the physical exchange of energy, water, materials, and by-products.

[ii] George T. Renner (1947). "Geography of Industrial Localization." *Economic Geography* 23(3): 167-189.

[iii] Pierre Desrochers of the University of Toronto has written numerous articles on historical examples of industrial symbiosis, including Victorian England. See Appendix C for more information.

Figure 2 Industrial symbiosis in Kalundborg, Denmark. Source: Marian Chertow.



The small city of Kalundborg, Denmark, provides the best-known current example of industrial symbiosis in action. The primary business partners include an oil refinery, power station, gypsum board facility, and a pharmaceutical company that literally share ground water, surface water, wastewater, steam, and fuel, and exchange a variety of by-products that become inputs in other processes. Symbiosis in Kalundborg has resulted in substantial economic and environmental benefits. Since the uncovering of Kalundborg's symbiosis in the early 1990s, scholars have been investigating many questions – why did this phenomenon occur in Kalundborg? Are there are other regions exhibiting industrial symbiosis? How can such systems be replicated? Are they strictly the product of self-organization by economic entities or can they be planned in a conscious way? Answering these critical questions requires the engagement of a variety of disciplines: economics, business, policy, environmental management, systems engineering, law, and planning, and these were represented at the Symposium.

Industrial Symbiosis Research Symposium

A growing number of researchers around the world have been working on issues related to industrial symbiosis, but rather than raise the academic debate to a new level, scholars pursuing different disciplinary paths often simply call similar phenomena by different names. When Marian Chertow proposed bringing together these researchers for the first global research conference on industrial symbiosis, colleagues from Kalundborg and across the world enthusiastically supported her suggestion, emphasizing the critical need for assessment and agenda-setting in this emerging area.

The Industrial Symbiosis Research Symposium brought together over thirty researchers from fifteen countries and a variety of disciplines, many of whom had done pioneering work related to symbiosis. The purpose of the Symposium was to give these researchers an opportunity to share their knowledge and experiences on the state of research, to determine areas of possible cross-fertilization among disciplines, and to establish research priorities.

Participants addressed a number of questions and issues over the course of the symposium:

- Is there a single definition of industrial symbiosis? If not, how does industrial symbiosis manifest itself?
- What are the patterns (regulatory, competitive, economic, and so forth) underlying the various forms of industrial symbiosis?
- What kind of tools (economic, planning, engineering) can help analyze and promote industrial symbiosis?

The Symposium took place over two days, January 7-9, 2004, at the Yale School of Forestry and Environmental Studies in New Haven, Connecticut, USA. Professor Chertow opened up the symposium with introductory remarks on the purpose of the symposium and research questions to frame discussion. Regional Round-Ups, following the introductory remarks, involved symposium participants in summarizing industrial symbiosis activity and research in their parts of the world. The rest of the Symposium was split into four focal area sessions: Modeling Industrial Ecosystems; Urban and Regional Planning; Multi-scale Analysis; and Economics and Business

Strategy. For each focal area, two symposium participants gave a presentation on their research. The presentations were complemented by a brief, moderated question-and-answer period. Moderated breakout sessions on each focal area followed the presentations. Participants joined the breakout session of their choice. The purpose of the breakout sessions was to discuss the presentations and determine major questions for further research in that focal area. At the end of the Symposium, participants gathered in a plenary session to discuss and debate the issues raised during the two days. The result was the identification of overarching questions and issues on industrial symbiosis that warrant further research.

This report summarizes the proceedings of the Symposium and suggests next steps for the associated research community. The following section summarizes the opening remarks, which laid out some of the challenges for the Symposium. The next section reports on industrial symbiosis activities around the world, by region, as well as crosscutting themes. The next four sections summarize the presentations and discussion regarding modeling industrial ecosystems, multi-scale analysis of symbiotic activities, economics and business strategy, and urban and regional planning systems. The final section synthesizes issues and questions identified by Symposium participants as needing further research.

OPENING SESSION

Marian Chertow, Yale University (United States)

The multi-disciplinary nature of industrial symbiosis means that researchers' backgrounds affect their perspectives on what symbiosis is, and how it can be replicated. For example, a standing debate in this area is on the importance of by-product exchange to industrial symbiosis: whether industrial symbiosis *is* by-product exchange; whether industrial symbiosis *includes* by-product exchange; or whether by-product exchange is *even a focal point* amidst a range of other values and activities. Historical elements that inform our views of industrial symbiosis include researchers' experiences with single-industry dominated complexes including chemicals and petrochemicals, pulp and paper, and sugar cane[iv]; agriculturally based integrated biosystems; waste management including mining and recycling; and those pursuing social and environmental improvement through sustainable development. Linkages across industries are characterized as:

- supply chain-related
- physical by-product exchanges
- utility and site-related exchanges
- additional shared services

Some common elements of IS are geographic proximity of partners, inter-organizational collaboration including with the host community, resource sharing, a mixture of industries, and a systems view recognizing the importance of synergistic material flows and a lifecycle perspective. There is a need for explicit recognition of various disciplinary antecedents and some form of a common vocabulary.

[iv] See, for example, Nelson L. Nemerow (1995). *Zero Pollution for Industry: Waste Minimization Through Industrial Complexes.* Wiley-Interscience.

Many key questions were raised as topics for the focal area sessions. Are symbiosis projects guided by a visible or invisible hand and what is the role of planning? How could researchers pursue multi-scale analysis and what emergent properties might be found? Are analytic models from other fields applicable for industrial symbiosis? What is the business case for industrial symbiosis and how does market behavior affect it? Finally, which topics hold the greatest potential for future research?

REGIONAL ROUND-UPS

Western Europe

David Gibbs, University of Hull (United Kingdom)

Roughly twenty industrial symbiosis projects are clustered throughout the United Kingdom, including important activities in Yorkshire, Scotland, and around London. In addition to local public sector initiatives, the UK Business Council for Sustainable Development (BCSD-UK) has been a major driver of industrial symbiosis activity. The National Industrial symbiosis Project (NISP – www.nisp.org.uk) is an important focal point. NISP has a core of physical activity taking place in the Humber sub-region and the West Midlands in England, plus a separate project in Scotland. According to the BCSD-UK, expected economic benefits for each region total £60 million over a five-year period. This includes 100,000 tons of waste per annum diverted from landfills, the creation of 100 new jobs and substantial reductions in water and energy use.

In the Netherlands more sites have been proposed and developed than is the case for the UK. Pellenbarg identifies 62 industrial symbiosis sites that have been encouraged to develop over the past ten years by the Dutch national government – these are a mixture of new developments and the revitalization of existing sites.[v] There are particular concentrations in the provinces of Gelderland, North Holland, and Utrecht. In his survey, Pellenbarg surveyed forty-three sites – more than half of these are in the project development stage. Some US$3.5 million was made available by the Dutch government for the period 1997-2003 for research, inventory and information projects on what are termed "sustainable business sites."

[v] P.H. Pellenbarg (2002). "Sustainable Business Sites in the Netherlands: A Survey of Policies and Experiences." *Journal of Environmental Planning and Management*, 45(1), 59-84.

Arnulf Hasler, Institute for Innovation and Environmental Management at the University of Graz (Austria)

In Austria, the term "industrial recycling network" is more commonly used than industrial symbiosis. In Austria, Germany, and Scandinavia, these networks involve recycling-oriented cooperation between independent firms from different industrial sectors, usually including the presence of material recyclers. The networks aim to reuse industrial and consumer waste materials as substitutes for raw material inputs and energy sources. Information gathering and distribution is viewed as a critical component in the functioning of the networks, especially in order to create a trusting atmosphere among the network partners. In the Austrian Federal State of Styria, for example, a database of over 200 waste streams exists in order to develop a recycling information network among firms that supports regional resource management. The database focuses on the following waste streams: wooden pallets, scrap granite, and scrap coating powder. A centralized Regional Recycling Information System (REGRIS) in the Oldenburger Münsterland Region in the northwest of Germany supports the management of recycling driven inter-company information flows and provides data to local firms about recycling opportunities and coordinates recycling activities.

Asia-Pacific Region

Jun Bi, Nanjing University (China)

In China, industrial symbiosis activities are being implemented through the idea of the "circular economy." The circular economy is a new model of economic development based on the principles of industrial ecology where economic and environmental systems are integrated. The cycling of resources is central to this notion of development. Theoretically, the circular economy is to be implemented through a "top-down approach" where the national and provincial governments plan the agricultural, industrial, service, and other sectors. In practice, these principles have been difficult to enforce as there is little understanding at the local level and insufficient guidelines as to how these principles are to be applied. The political and economic driving forces behind the circular economy in China are not yet clear. Circular economy activities are still in the pilot stage in China, though numerous eco-industrial parks have been successfully implemented. Examples include: Guangxi Guigang Industrial Park (sugar industry); Guangdong Nanhai Environmental Technology Park; and Suzhou-Singapore Eco-Industrial Park.

Figure 3 By-products of Guitang Group, sugar and paper mill, Guigang City, China. © 2004. Photo credit: Ernest Lowe.

Rene van Berkel, Curtin University (Australia)

Australia has generally approached industrial symbiosis through industry planning and waste exchanges. However, other drivers for a new approach to industrial symbiosis are emerging. These drivers include: (1) the large number of by-products associated with minerals processing; (2) degraded land and dryland salinity; and (3) drought and water restrictions. To address these concerns, some entities are taking advantage of "low-hanging fruit" activities including by-product use and cogeneration. In order to engage in more complex symbiotic systems, however, new technological and engineering tools and approaches need to be developed. Engineering tools and technologies require adaptation to realize these kinds of exchanges. This conclusion is supported by studies conducted by the Australian Research Council. The Council's research has focused on technology, energy, structural, and organizational arrangements related to implementing industrial symbiosis projects.

South Asia

Ramesh Ramaswamy, Technology Exchange Network (India)

The Indian context is very different from that of the U.S. and Europe. The country is very poor, has a large population, and has limited resources. The pattern of industrialization is such that it is dominated by millions of small-scale "informal" production units. The flows of material through the informal sector are much larger than the flows through the organized industrial sector. Hence, any strategy for implementation of industrial ecology or industrial symbiosis has to factor in the informal sector to have any large-scale impact.

Although there is a significant amount of recycling and re-use at the micro-level and there is a strong culture of re-using and recycling, it is often poorly regulated and unsafe. There is neither a formal symbiosis, nor are there any eco-industrial parks (EIPs), although there are numerous instances of informal undocumented symbiosis (e.g. municipal sewage is recycled for industrial use in Chennai).

In order to institutionalize industrial symbiosis in India, it needs to be introduced as an element in the formal planning system with a focus on resource optimization. Special accent could be placed on issues concerning energy, water and land – resources that are in very short supply in the country.

North America

Raymond Côté, Dalhousie University (Canada)

There is a growth in eco-industrial activity in Canada. The activities in most provinces are in the form of eco-industrial parks and by-product re-use. Different groups are planning roles in increasing Canadian industrial symbiosis activity: regional development agencies, municipalities, universities and industry. A liquefied natural gas company, for example, has supported an industrial symbiosis study involving their proposed facility in Nova Scotia. Local governments have also supported eco-industrial networking studies in the past year in Saskatchewan, Alberta and British Columbia. Research on industrial symbiosis has mostly been conducted through universities although some consulting companies are getting involved. One new eco-industrial consulting firm comprising graduates from Dalhousie's program has been established. A big hurdle in Canada is minimal federal government interest and support.

Judy Kincaid, Triangle J Council of Governments, Research Triangle Park, North Carolina (United States)

Drawing the line between industrial symbiosis and eco-industrial parks (EIPs) is difficult. If one takes a broader view of IS beyond eco-industrial parks, a lot of IS activities are occurring in the United States. For example, there are 340 landfill gas reuse projects in the U.S. In one of these projects in North Carolina, landfill gas heats water for greenhouses and heats kilns for glass studios. This broad view of IS includes (1) eco-industrial parks in Londonderry, New Hampshire; Devens, Massachusetts; and Cape Charles, Virginia; (2) eco-industrial buildings in Chicago and Minneapolis; (3) a resource recovery park in Indio, California; (4) dozens of by-product synergy projects; (5) hundreds of landfill gas to energy projects; and (6) hundreds of waste exchanges. This local experience should be translated to the national level. There are numerous opportunities to create links between local communities with symbiosis-like projects to other communities that have not yet implemented such projects.

Africa and Latin America

Weslynne Ashton, Yale University (United States)

There are a few examples of industrial ecology and symbiosis activities in Africa. The Tunweni Brewery in Namibia in 1997 was an "integrated bio-system" initiative of the United Nations University in Japan. The Nuclear Energy Corporation of South Africa owns and manages an eco-industrial park with over eighty tenants with shared services, including recycling, but no by-product exchanges. A recently formed association of professionals and academics from Kenya, Mauritius, South Africa, and Egypt is working to promote industrial ecology concepts and projects throughout the continent.

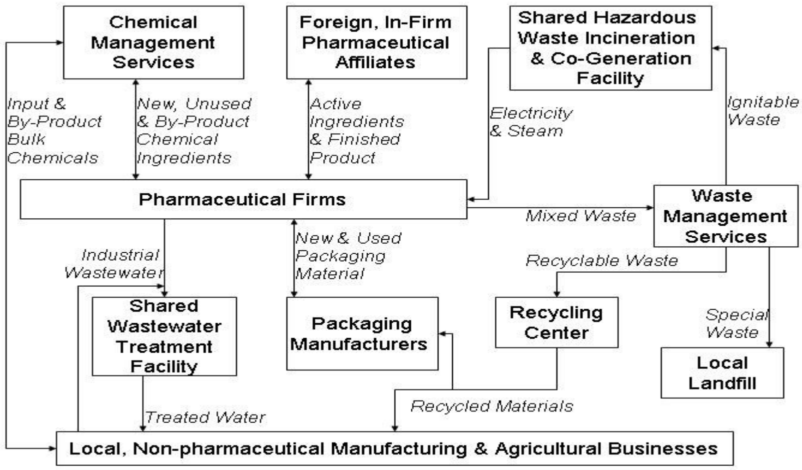
In Latin America, both academic researchers and practitioners are exploring opportunities for implementing symbiosis in Chile[vi], Honduras, and the Caribbean (Puerto Rico, Trinidad and Tobago, Jamaica, and Haiti), although full-blown symbiotic networks have not yet been identified. In general, in the Caribbean, studies are taking place with university partners. A Canadian professor is collaborating with faculty at the University of the West Indies in Trinidad to develop eco-industrial park studies. A professor at the University of the West Indies in Jamaica and colleagues have developed an electronic waste exchange system to be tested for applicability in developing countries like Jamaica. A researcher at the University of Technology at Troyes, France is leading a study to implement a sugar cane eco-complex in Haiti.

Puerto Rico presents an interesting example, as numerous symbiotic linkages have been uncovered around the island in a variety of industrial sectors, which suggests

[vi] Ms. Ana Maria Ruz. "Real Problems for Applying Industrial Ecology Concepts" at Second International Society for Industral Ecology Conference, Ann Arbor, Michigan. June 2003.

that such activities may already be taking place in other parts of the region and are not yet known. Current trends in these parts of the world that can be used to promote the industrial symbiosis concept are: a growing environmental awareness in industry; emphasis on industry clusters for economic development; the need to identify symbiosis that already exists; and academic and practical interest in exploring these opportunities.

Figure 4 Eco-Industrial Activities in the Barceloneta Pharmaceutical Cluster, Puerto Rico. Source: Weslynne Ashton



Cross-Cutting Themes

Leo Baas of Erasmus University in the Netherlands commented that there were several similarities between the adoption of industrial symbiosis and cleaner production. These similarities include anecdotal evidence from several successful case studies but little adoption at a large scale. Industrial symbiosis, as defined as by-product exchange, has the added difficulty of operating across organizations. It would be useful to examine industrial symbiosis from a lifecycle perspective. This would help answer questions such as whether Kalundborg and other examples of industrial symbiosis are at early or mature stages of growth. To answer these kinds of questions, much more knowledge and shared information is needed.

Ernie Lowe of Indigo Development in the United States stressed that industrial symbiosis is one aspect of improving the efficiency of resource use in industry. He suggested that researchers and practitioners needed to explore related system concepts and revisit the eco-industrial park concept.

Reid Lifset, editor of the *Journal of Industrial Ecology*, highlighted the large regional differences in the conceptualization and implementation of IS. He challenged the conference participants with these questions:

- What is the environmental benefit of IS? Does it address the most important environmental problems and are there tradeoffs with pollution prevention/cleaner production?

- How do we implement industrial symbiosis, including the need to investigate failures?
- Does lock-in to old technologies occur from industrial symbiosis?

FOCAL AREA SESSION IA: MODELING INDUSTRIAL ECOSYSTEMS

Approach

The focal session on modeling industrial ecosystems aimed at assessing the quality of predictive tools that can be applied to industrial ecosystems. The approach to this assessment is to examine the current state of and research needs for systems that model materials and waste exchanges, by-product optimization, potential impact mitigation, and individual agent actions. These systems attempt to predict behavior, interactions, and network sustainability, as well as analyze corollaries from business, engineering, and ecological systems modeling.

Focal Area Presentations

Clinton Andrews, Rutgers University (United States)

Professor Andrews presented the process of including "agency" into industrial symbiosis models — in the other words, adding the "who" to the "what" in industrial ecology. He argued that this is useful because human behavior is at least as important a determinant of environmental outcomes as technological factors, and also because it highlights the need for and value of individual action. Professor Andrews began his talk with a caveat regarding his assignment to assess models as predictive tools in industrial symbiosis research. He noted that while models may help in predictions, models do not offer policy prescriptions. When including agency into symbiosis models, one must choose, along several dimensions, what kind of agent is to be modeled: (1) smart or dumb, (2) dynamic or static, (3) individual or collective, and (4) driven by agency or structure. With regard to dynamic or static models, it should be noted that most economic models show agents with static preferences and static characteristics. There are very few "realistic" models out there that account for agents with evolving preferences and characteristics.

Agent-based modeling is a computer simulation technique made possible by object-oriented programming languages, such as C++, Java, etc. Agent-based models represent systemic actors as software objects, allowing them to interact and evolve. The result is a bottom-up view of a complex system such as a firm or a city. Professor Andrews is currently involved in an organizational behavior modeling project that builds on multi-agent models of firms and includes environmental performance. The purpose of the project is to explore ways to understand principal-agent problems in environmental management. The project is taking a staged approach from a single-establishment firm, to a branch plant, to the supply chain, and then to the sector. The ultimate goal is to create a model that can provide credible scenarios or answers to policy makers regarding environmental management issues.

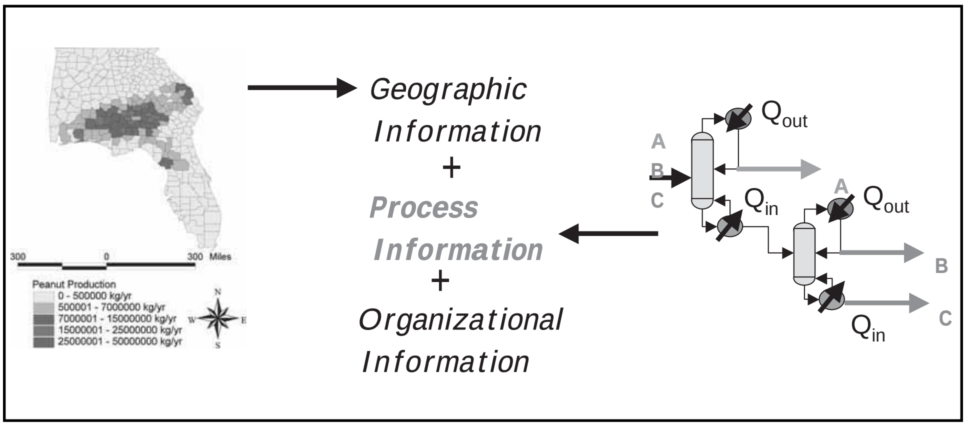
Professor Andrews presented four illustrative projects to demonstrate the utility of agency modeling as a predictive tool. First, a model illustrating the tragedy of the commons — where the agents are individual, rational actors with static preferences — is a good predictor of actual behavior although it has little value as a prescriptive tool. Second, a model illustrating state-level electricity restructuring policies — where the agents are adaptive collective rational actors — is a good predictor of actual behavior, but only works in a narrow context and has crude value as a prescriptive tool. Third, a model illustrating collective management of animal wastes by farms — where agents are myopic rational firms with static preferences — is an acceptable predictor. The model is better for understanding the merits of informational prescriptions. Fourth, a model for predicting failures of pollution prevention activities — where models are myopic rational individuals within firms — is an acceptable predictor. It is good for testing alternative prescriptions of many types.

The results of the research so far emphasize that modeling is really an elaborated type of formal theorizing. Organizational behavior, due to its complexity, still poses a considerable modeling challenge, and the underlying technology characteristics still need to be modeled accurately.

Matthew Realff, Georgia Institute of Technology (United States)

Professor Realff discussed the integration of process modeling into industrial symbiosis. Process systems engineering is concerned with designing processes in a facility so that they are as efficient as possible (e.g. to minimize costs, heat loss, and so forth). Process engineers model different design options for creating a given product with known input materials in order to see which option is most desirable. Informing the model is a number of "superstructures," which combine available technologies and processes. These superstructures set the parameters for modeling. The modeler then uses process modeling software to optimize choices and options.

Figure 5 Schematic integrating geographic, process, and organizational information for industrial symbiosis. Source: Matthew Realff.



Professor Realff posed the question of whether these superstructures and the engineering method can be applied to modeling industrial symbiosis. The advantage of using the process systems method is that it provides the best engineering solution, i.e. it is the most efficient design. The disadvantage is that traditional engineering models do not include parameters important to industrial symbiosis, such as organization, individuals, time, and access to resources. These kinds of parameters, particularly geographical and organizational information, need to be included in order for modeling to be more relevant to industrial symbiosis. Forces outside the modeled system should also be included if they will affect decision-making.

Breakout Session Discussion

Moderator: Thomas Graedel, Yale University (United States)

The breakout session on modeling focused on whether models are useful and how models can be modified to improve prospects for industrial symbiosis. The general conclusion was that while models generally cannot reveal answers to all questions, they are useful to inform debates about industrial symbiosis. For instance, models can be used to guide policy making and inform stakeholders. Because modeling is a common language spoken among engineers, it can be used to facilitate communication among firms. One participant pointed out that the process of model building can unveil hidden assumptions.

Specific questions about modeling industrial ecosystems warranting future research included:

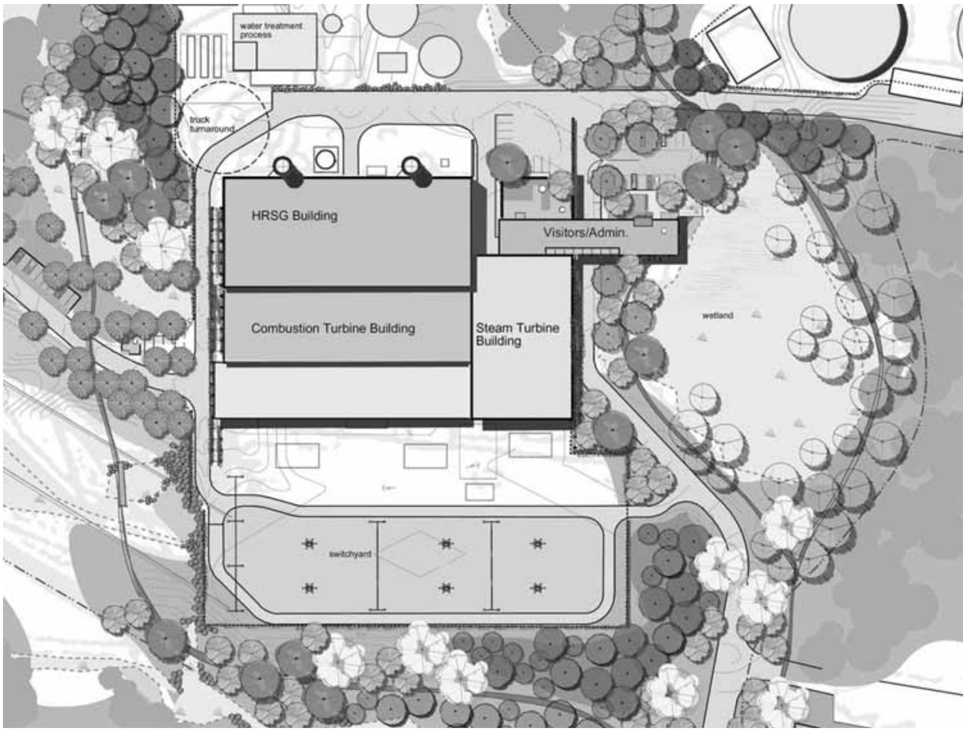
- Can the history of Kalundborg be modeled? If so, what would the model reveal about the future of Kalundborg?
- How can process models be linked with social elements, such as economic indicators, agent behavior, and trust?
- Should engineering and social models be linked? Or should one model be developed that includes all variables?
- Is it cost-effective to develop such complex models?

FOCAL AREA SESSION IB: URBAN AND REGIONAL PLANNING

Approach

The focal session on urban and regional planning aimed at describing the role of industrial symbiosis in regional systems and examining institutional (planned) initiatives for its implementation. The approach to describing this role is multi-faceted. The approach involves (1) analyzing the spatial aspects of industrial symbiosis and their potential contribution to achieving urban and regional planning goals; (2) assessing optimal timing for industrial symbiosis input into planning processes; (3) analyzing changes necessary in current practices to incorporate industrial symbiosis into planning and policy; (4) addressing the role of communities and institutional actors in evolving current business practices; (5) addressing the role of regulation in by-product exchange; (6) examining policy goals and incentives; and (7) placing industrial symbiosis in the context of regional/national resource (water, waste, energy) policy.

Figure 6 Plan drawing of the AES Cogeneration Facility Londonderry, New Hampshire, 2000. Source: Michael Singer.



Focal Area Presentations

Tsuyoshi Fujita, Toyo University (Japan)

Professor Fujita gave a presentation on integrating industrial symbiosis into systems planning, using examples from Japanese eco-industrial parks and "eco-towns." He described an industrial symbiosis modeling tool for planners that incorporates Geographic Information Systems and material flow data. The model allows planners to input how much material is going to certain locations in order to assist in determining what symbiotic connections and resource efficiency improvements can be made. A systems planning model for the Muko River Basin was created to incorporate IS concepts. It began with specifying inventories of organic wastes and biomass resources that flow through the following sectors: agriculture, livestock, food processing, food retail, households, and the forestry park service. Liquid and solid organic wastes and CO_2 emissions were tracked through processing and treatment. The model placed material flow data into a Geographic Information System for the region. The model is able to: (1) identify points of consumption and emission; (2)

quantify the thermal potential of organic material in source points for methane fermentation; (3) map household demands for heat (with an aim to matching thermal potential of organic materials with household heat demand); and (4) identify areas where methane fermentation is a suitable policy option for power. A similar methodology has been used to identify regions where construction and demolition waste can be used to meet demands for construction materials in the city of Osaka. The development of future methodologies for system planning must include the ability to vary temporal scales and to model different policy options.

Jouni Korhonen, University of Tampere (Finland)

Professor Korhonen's work deals with the application of industrial ecology principles. He is particularly interested in how the concept of "roundput," or the cooperative utilisation of waste material, renewables and waste energy in the industrial system, can lead to environmental and economic wins at both the input and output interfaces with the natural system. The forest sector is a major player in Finland's economy, with forest products/by-products used to meet 70 percent of the nation's energy demand. In Finnish cities, such as Jyväskylä, it is common to cogenerate electricity from forest by-products and use the waste heat for district and industrial heating, process steam and agriculture. Regional planners must consider the performance of system components as well as the system as a whole. For example, maximizing paper exports (90 percent of paper produced in Finland is exported) might be at odds with maximizing the efficiency of resource use in the regional industrial ecosystem. Industrial ecologists thus face a siginificant challenge in ensuring that in promoting the regional industrial ecosystem concept, they also consider system boundaries, individual system components, and eco-efficiency vs. growth.

Breakout Session Discussion

Moderator: Stefan Anderberg, University of Copenhagen (Denmark)

The participants in the breakout session on urban and regional planning first synthesized current knowledge on the subject and then posed questions for future research. Past experience has shown that there are three conditions usually present for eco-industrial developments to take shape. First, there have to be industries willing to occupy specific "niches." Second, there has to be interest from a public agency, usually local economic development offices or regional/local planning departments, to help facilitate the partnerships. Third, the policy environment and/or operating context can foster eco-industrial development, such as landfill bans and high tipping fees, high energy prices, or scarce water and material resources. Nevertheless, many participants acknowledge that many networks emerge spontaneously without formed planning processes.

The group then discussed how to promote industrial symbiosis within a planning context. The first step is to discover the places or the contexts in which industrial symbiosis activities have a large, positive impact. This impact could occur in the economic, environmental, or other realm. This impact should be quantified and presented to policy makers as a positive case for industrial symbiosis implementation. The second step is to target a "facilitator" or "champion" of the proposed symbiosis plan. This champion could be, for example, the city planning department or local chamber of commerce, a company, or even an individual. The group emphasized that the champion should coordinate or facilitate partnerships rather than planning them. The coordinating function is important in bringing all of the important industrial symbiosis players together. The objectives of eco-industrial developments should be clear at all times, whether driven by corporate profitability, economic development, or resource optimization/conservation.

The participants identified critical research questions regarding urban and regional planning in the context of developing industrial symbiosis networks:

- What are the (public) benefits of industrial symbiosis and how are they measured? What metrics can be developed to measure benefits?
- What are the regulatory/policy drivers of industrial symbiosis?
- What is the role for quantitative versus qualitative research on industrial symbiosis and how can it be applied in planning?
- To what extent do planning and market forces create the most efficient symbiosis systems?
- What is the role of case studies? Case studies should be collected that examine eco-industrial developments or industrial symbiosis networks that had different objectives (profitability, resource conservation, and so forth), and the methods used to attain those goals. Both successes and failures and the reasons for particular outcomes should be studied.
- What cultural mechanisms in different countries promote industrial symbiosis?
- What is the appropriate role of government in planning and implementing industrial symbiosis activities?
- A vision of industrial symbiosis in the year 2020 should be developed. How would industrial symbiosis adopted broadly look in 2020? What policy tools are necessary to achieve that vision?

FOCAL AREA SESSION IIA: MULTI-SCALE ANALYSIS

Approach

The purpose of multi-scale analysis is to examine insights that are not apparent when examining industrial ecosystems along a single level or scale. Multi-scale analysis is achieved through analyzing the impacts of actors' behavior, relationships, and exchanges within and across the boundaries of different levels along multiple scales. These scale dimensions include, for example, spatial (micro, meso, and macro); temporal (time horizons, dynamic behavior over time); and organizational. The analysis of these dimensions can be quantitative and qualitative. Cross-level and cross-scale phenomena, emergent properties, and complexity in industrial ecosystems are examined.

Focal Area Presentations

Stephen Levine, Tufts University (United States)

Professor Levine examined scale from an organizational perspective by comparing and contrasting competition and symbiosis in natural and industrial ecosystems. In natural ecosystems, organisms interact in a variety of ways. Material transfer is primarily due to predator-prey interactions, where one organism benefits and the other loses. This is an involuntary transfer, in contrast to the voluntary exchange of material for money that characterizes industrial systems and is beneficial to both parties. Resource competition in natural systems follows as a natural outcome of the predator-prey interaction. Sometimes the interactions in natural systems are symbiotic and both organisms benefit. In industrial ecosystems, where the entities interact on a voluntary basis, their relationships are not easily categorized as "competitive" or "symbiotic." For example, at one level, industrial entities compete for the same market of buyers. At another level, however, if all the actors in a similar industry demand more of a particular resource, they all benefit because suppliers will increase the supply of that resource. Furthermore, in industrial symbiosis networks, entities can arrange relationships that provide mutual benefit through the sharing of resources.

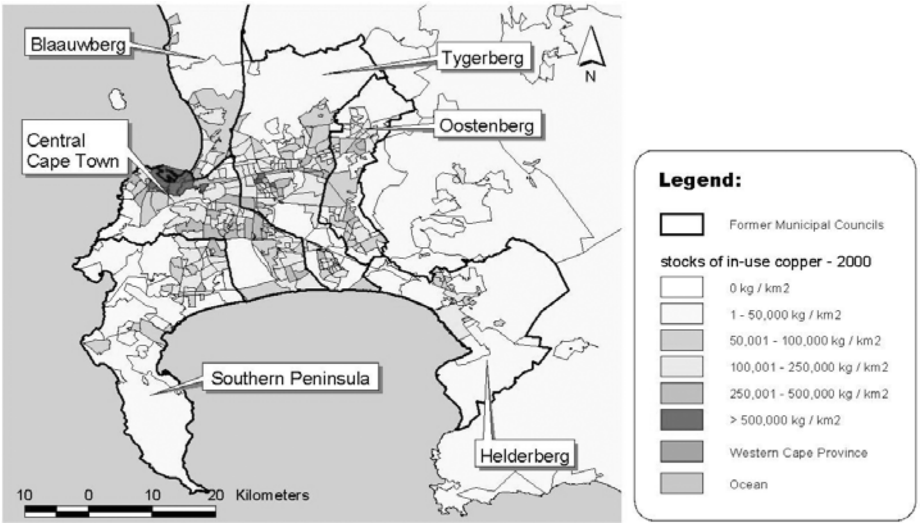
Professor Levine argued that the differences manifest themselves in the kinds of feedback loops associated with ecological and industrial relationships. Ecological systems are largely characterized by negative feedback loops. These types of systems exhibit considerable "internal control," that is, they are resistant to external forces. Industrial systems, in contrast, are characterized by positive feedback loops. These types of systems generally require external control and need manipulation by outside forces. As a result, systems dominated by positive feedback loops need much more management. Finally, in nature or in industry, competition can negatively affect the individual but can positively affect the system.

Thomas Graedel, Yale University (United States)

Professor Graedel discussed his research on stocks and flows. The study examines flows of various metals at different spatial levels – local, state, national, regional, and global. The goal of the study is to assess materials flows at the national level, to aggregate data at nine regional levels, and then to present a global picture. Researchers perform the stocks and flows analysis by identifying and quantifying metal reservoirs, production, consumption, imports, exports, and waste.

Professor Graedel presented the results of a study of copper flows on the African continent and in Oceania. A case study of Cape Town, South Africa, demonstrated varying concentrations of in-use copper stocks throughout the city. Mapping these concentrations enabled analysis of differences in copper use among neighborhoods to show how wealth and class affects copper stocks and flows. The map also demonstrated the richness that Geographic Information Systems (GIS) mapping tools add to spatial scale analyses. GIS enables researchers to break down data and provide policy recommendations at a local level. One might not be able to offer targeted policy options if the data were only available at the aggregate level. The study in Cape Town, for example, revealed that policies aimed at reusing copper in Cape Town should be concentrated on poorer residential areas and industrial areas given the high concentrations of materials there, rather than in wealthy areas. Similarly, a study in Sydney, Australia revealed that copper reuse programs should concentrate on central urban areas and not on a national approach.

Figure 7 Spatial distribution of copper stocks in Cape Town, South Africa. Source: Dick van Beers.



Professor Graedel concluded his presentation by commenting that industrial symbiosis research should not be limited to a single spatial level. Limited analysis may result in researchers missing some of the most interesting and useful information. He recommended that industrial symbiosis researchers develop approaches for improved analysis of stocks and flows, especially at the level of urban and industrial ecosystems.

Breakout Session Discussion

Moderator: Helge Brattebø, Norwegian Technical University (Norway)

The breakout session on multi-scale analysis covered a wide range of issues. The primary question revolved around how an industrial symbiosis researcher picks the correct scale in analyzing a symbiotic network. If the scale of analysis is too small, the researcher does not have a viable analytic unit. Analysis at a large scale, however, can become too complex and not useful. To some extent, the technology that is available – such as modeling software or GIS technology – helps define the scale that is used. The participants generally agreed that there is a need in industrial symbiosis research to move beyond the facility level and start thinking about symbiotic networks at a larger level, such as regionally or nationally. Participants also discussed the need to incorporate time and information into multi-scale analysis.

With regard to information, industrial systems have an information flow network that sits on top of other systems. However, information flow networks incorporated in industrial systems do not typically appear in the ecological literature on symbiosis. Future research should consider how information flows can be modeled into systems. With regard to time, participants discussed how temporal scale analysis affects the measurement of benefits from industrial symbiosis. For instance, environmental benefits of industrial symbiosis activities, as in Kalundborg, might not be realized for a long period after implementation. Analyses that integrate a longer time horizon might be better equipped to recognize benefits. Furthermore, the question of time suggests that public policy frameworks can help prevent the benefits of symbiosis from being too heavily discounted.

The participants identified these critical research questions regarding multi-scale analysis in the context of developing industrial symbiosis networks:

- How does an industrial symbiosis researcher pick the appropriate scale in analyzing a symbiotic relationship?
- What kinds of data and tools are needed to move analysis beyond the facility level, such as to the regional or national level?
- What kinds of technologies and computer models can be used to assist multi-scale analysis?
- How can time and information flows be incorporated into multi-scale analysis?

FOCAL AREA SESSION IIB: ECONOMICS AND BUSINESS STRATEGY

Approach

The focal session on economics and business strategy aimed to evaluate the position of industrial symbiosis in current economic thought. The speakers in this session analyzed the business strategy dimensions of industrial symbiosis (competitive advantages, networking, cooperative approaches), and contractual issues as well as economic impacts of industrial symbiosis relationships (avoided costs, profitability trends, potential of technological obsolescence over the long-term of a contract). They also examined how current economic systems foster and/or inhibit industrial symbiosis relationships and what changes are necessary to support industrial symbiosis in the business community.

Focal Area Presentations

John Ehrenfeld, International Society for Industrial Ecology (United States)

Dr. Ehrenfeld of the International Society for Industrial Ecology (ISIE) moderated the session. His opening remarks revolved around the challenges of introducing industrial symbiosis networks into the market. Industrial symbiosis networks are usually self-organized – meaning that they are brought about almost entirely by market forces. They differ, however, from standard industrial networks in that they provide both private and public goods (such as positive environmental benefits). In order for IS networks to be established, they must meet rational decision-making criteria by their implementers. These include technical feasibility and the achievement of both economic and environmental benefits. Factors that affect whether firms pursue industrial symbiosis networks include extent of transaction costs, supply chain disruption risks, the degree of senior management interest, regulatory prohibitions and disincentives, stakeholder interest, shareholder support, and liabilities arising from regulation. Future research should focus on the nexus between policy development and market forces. The development and implementation of policy needs to be informed by market functioning and firm behavior. Specifically, policies should create a context for industrial symbiosis evolution over a long period rather than the one-time planning of a project.

Jørgen Christensen, Symbiosis Institute, Kalundborg, and Noel Jacobsen, Roskilde University (Denmark)

Mr. Christensen and Mr. Jacobsen, who participated by telephone, presented lessons learned from the Kalundborg, Denmark industrial symbiosis experience and insights into future research. Kalundborg remains the best known example of industrial symbiosis, as the system continues to evolve in light of changes in materials used, firm ownership and policy changes.

The presenters outlined the general pattern in firm level decision-making around adoption of industrial symbiosis, based on the Kalundborg experience. At first, companies evaluate their own situation with regard to expected regulatory changes that might affect the disposal of particular by-products. The company then considers the value of those by-products and the potential value of exchanging them with another party. In order to evaluate an exchange, the firms have to assess the economics of it and examine the regulations that would guide their actions. They then have to receive approval from authorities and when approved, conduct tests and then do full scale implementation. The procedure, however, has been less systematic in most cases. In the case of Kalundborg, the timeframe for implementation of certain exchanges was long. For example, one gas exchange among companies took seven years to negotiate; one exchange of cooling water and steam took six years. In some cases there were longer implementation times due to periods of dormancy.

It was emphasized that an industrial symbiosis project requires an idea, but also the following crucial elements: a pre-existing knowledge of potential partners, technical considerations, economic considerations, contracts, and implementation.

Mr. Christensen stressed that good communication is critical to the success of symbiosis. Communication in Kalundborg was facilitated by the small size of the community involved, the already established acquaintance of the managers, the open, non-secretive management style of the companies, the absence of competitors locally, and opportunities for cooperation in projects. The contractual relationships that developed were also very important. Mr. Jacobsen, based on his research, found that the contracts were detailed regarding the interaction of firms and the flow of materials. Mechanisms for future changes were included, such as escape clauses and requirements for upgrading. He noted that the symbiosis-related contracts used in Kalundborg are very similar to regular contracts except that they may have a greater level of detail. The symbiosis contracts include elements such as terms of delivery for by-products (e.g. period, quality, quantity); price and payment terms; force majeure clauses; and options for future changes (e.g. escape clauses, requirements for upgrading, and so forth).

The lessons to be learned from Kalundborg include the following:

- The Kalundborg symbiosis network emerged spontaneously;
- The network developed out of economic incentives; the environmental aspects of industrial symbiosis emerged later;
- Good communication has been more important for success than technology;
- Interdependence between the partners has never been a problem;
- Regulation has created incentives but has also – in a few cases – created difficulties for good solutions;
- Legislation in certain countries may prevent good solutions;
- Kalundborg can be a model for other industrial symbisois projects.

Rachel Lombardi, Yale University (United States)

Dr. Lombardi gave a presentation on an industrial symbiosis network developing in Guayama, Puerto Rico. There are similar industrial players in Guayama as in Kalundborg: a power station, a petrochemical refinery, pharmaceutical plants, and a waste water treament plant, among others. Several symbiotic linkages have developed due to the needs of the power plant and the limited availability of water in Guayama. The presence of a suitable water supply is viewed as critical for the siting and permitting of new power plants in Puerto Rico. AES, a global power generator, sited its new coal-powered, circulating fluidized bed cogeneration plant close to a wastewater treatment plant in order to use reclaimed water. AES's use of reclaimed water has resulted in four million gallons per day of avoided freshwater extraction at approximately \$1.4 million of savings per year. In turn, AES provides steam to the adjacent refinery, which has shut down its old oil-fired boilers that were previously used for steam generation. The net savings of these symbiotic activities for all partners is approximately \$420,000 to \$670,000 annually. The lessons learned from the Guayama experience are that symbiosis has been driven by resource needs, particularly water and energy, and favorable economics. The symbiosis also allowed AES "license to operate," that is, to undertake a business opportunity that would have been impossible otherwise.

Breakout Session Discussion

Moderator: John Ehrenfeld, International Society for Industrial Ecology (United States)

The participants' discussion in the break-out session revolved around developing a better understanding of the process of establishing industrial symbiosis networks among firms, as well as determining the role played by third parties in facilitating those relationships, and quantifying both the economic and environmental benefits of industrial symbiosis networks.

Specific questions and observations on economic and business strategy warranting future research included:

- Does the contractual "lock-in" of symbiotic relationships make the implementation of industrial symbiosis networks more difficult or problematic?
- The economic, social, and environmental benefits of industrial symbiosis need to be better quantified. Such quantification can be useful in making the case, at the business and policymaker levels, for implementing industrial symbiosis. The question of setting boundaries in measuring benefits also needs to be addressed. The two presentations on Kalundborg and Guayama offered good progress on quantification of benefits.
- Which individuals or organizations are involved in the communication and networking involved in establishing IS networks? What are the context and dynamics for these interactions?
- How important is the diversity of firms (and their associated material flows) for establishing of industrial symbiosis networks? Do single-industry complexes count as symbiosis?
- How important is public funding in the development of industrial symbiosis networks? What types of public funding can support the development of industrial symbiosis networks? What role could public funds play when industrial symbiosis activities are not immediately economically favorable for companies, but would produce public goods?
- How can the processes businesses undertake in making the decision about engaging in an industrial symbiosis network be characterized?
- How is risk distributed among firms in industrial symbiosis networks?

SYNTHESIS: ISSUES FOR FURTHER RESEARCH

Several themes emerged in the discussions over the two-day symposium. These themes emerged from the four focal area presentations and their accompanying breakout sessions. These themes represent crucial areas requiring further study to improve understanding of the phenomenon of symbiosis and to create strategies for its implementation in a variety of settings. Below, each theme is briefly introduced with suggestions for research questions and topics.

Definition of Industrial Symbiosis

There was much discourse on what constitutes industrial symbiosis, starting with the various evolutionary strands from several disciplines that have seemingly converged in this phenomenon. No resolution was reached on "What is industrial symbiosis?" or whether we need to have a uniform definition of industrial symbiosis for the field to progress. Key issues were:

- Do we need a single definition? Is industrial symbiosis more than material exchanges, and if so, what else? Is there a single end-point at which industrial symbiosis systems converge? What characteristics of an industrial system qualify it as a symbiotic system? Is industrial symbiosis an end in and of itself?
- Issues of scale were seen as important for future research, particularly the need to determine appropriate systems boundaries for defining industrial symbiosis and understanding spatial contributions to the dynamics of industrial symbiosis systems.
- Several researchers highlighted the need to place industrial symbiosis within the larger context of sustainable industrial development as well as various global economic and environmental activities.
- Industrial symbiosis, like industrial ecology, is most relevant to the environmental arm of sustainable development, but the exact links to sustainable development need further exploration and clarification.
- Similarly, although there are obvious connections, industrial symbiosis researchers have not said much about global production and consumption systems or global supply chains. These global business dimensions require exploration.

Figure 8 Water Re-use in Thailand. © 2004. Photo credit: Andreas Koenig.

Implementation: Lessons and Barriers

With a growing number of industrial symbiosis examples in different countries, there is an opportunity to identify characteristics of industrial symbiosis systems and the factors that enable their implementation.

Key drivers

- What are the key drivers of industrial symbiosis? Are they purely economic? What are the roles of communication and various types of actors, such as individual champions?

Agents / Actors

- What are key characteristics of agents/actors who move industrial symbiosis forward? Is there a particular set of industry-types or industry-mixes that are more amenable to industrial symbiosis?

Economics and business

- In addition to understanding the economic drivers and business organizational aspects needed for the implementation of industrial symbiosis, several economic challenges have been identified. Questions regarding these challenges include:
  - How important are economic barriers to implementing industrial symbiosis, particularly concerns about technological lock-in or obsolescence? Is there a potential for industrial symbiosis to stifle innovation by responding too slowly to rapid changes in business dimensions?

   - The nature of public and private goods in industrial symbiosis activities needs to be better understood, particularly who benefits from and who bears the burden of providing associated public goods. Also in need of clarification are the motivations or justifications for private firms to provide public goods.

Planning

- Many efforts have begun to implement industrial symbiosis through planning by public sector institutions. Some of these have been successful. There is recognition that some degree of government participation is highly desirable.
   - Regional and urban planning models that are prescriptive in regard to sustainable development should be developed.
   - Economic and land-use planning disciplines should be integrated with an understanding of how industrial symbiosis fits into both of them.
   - The benefits of top-down vs. bottom-up approaches, especially in particular contexts should be investigated in order to understand (and subsequently propose) appropriate approaches for industrial symbiosis implementation in different regulatory environments (such as the centralized planning regime in China).

Cultural / legal context

- Many participants felt that cultural and legal factors in the design and implementation of industrial symbiosis activities deserved greater attention from researchers.
   - Research is warranted that describes and attempts to understand the different manifestations of industrial symbiosis in developed and developing countries, as well as how to apply industrial symbiosis principles to different parts of the world.
   - Research should be pursued that attempts to understand the types of regulatory structures that are beneficial to the development of industrial symbiosis activities.
   - Investigations into the relationships between key players (government, business, other social network actors) can also illustrate the dynamics of human actions in industrial symbiosis systems.
   - How do institutions and legal systems interact? How do these interactions differ across countries and how do these differences affect economic development?
   - Research into whether different drivers exist for industrial symbiosis activities in different contexts should also be undertaken.

Quantification

Industrial symbiosis has been touted as offering both environmental and economic benefits to the participants in the networks, but there have been few studies that document and quantify these benefits.

- *Measurement of benefits from industrial symbiosis activities*: Studies need to be conducted that can measure the economic gains and savings and environmental improvements within an industrial symbiosis network. There was also a call for measuring the public versus private benefits and identifying to whom the benefits in such systems accrue.
- *Measurement of significance of benefits*: Some concern was raised that, even when the benefits of industrial symbiosis are quantified, the relative benefits to the overall environmental impact of operations would be insignificant. Therefore, there is a need to quantify the size of environmental and economic earnings relative to the overall environmental impacts and economic revenues earned.
- *Contribution of industrial symbiosis toward sustainable development*: Related to the previous two questions, this topic aims to understand how IS contributes to larger goals of sustainable development. Some of the questions that need to be answered here include how resource optimization occurs at various organizational levels, from the individual facility to local industrial ecosystem to the broader region, and what the implications are of such optimization for sustainability.
- *Social benefits*: An important question is: How does industrial symbiosis benefit the human communities in which the systems are located? Can these benefits be quantified in economic and environmental terms or in other dimensions (e.g. is there an increase in social capital in communities with industrial symbiosis)?
- *Modeling*: Modeling is a useful tool through which researchers can test numerous ideas and hypotheses about industrial symbiosis, as well as construct systems that are optimized along particular parameters. One of the areas where modeling can be useful is examining the contribution of industrial symbiosis toward resource optimization at different levels and on multiple scales. Models can also be used to indicate potential symbiotic linkages and exchanges among actors in a system and also as a management tool. One idea that received much attention was the integration of models from various disciplines to explore how different components of a symbiotic system all come together. Different types of models that can be used include nested, agent-based, and integrated assessment.

Role of Other Disciplines

Many disciplines and types of organizations were not present in this meeting of primarily academic researchers and a few professional industrial symbiosis developers. Participants were asked to identify what contributions they envisioned could be made by those outside of the core industrial symbiosis community.

- NGOs and communities often serve as stakeholders who exert pressure on firms to engage in environmental activities. What, if any, role do they play in industrial symbiosis developments?
- Lawyers, legal experts and regulators could contribute their intricate knowledge of legal systems to improve understanding of legal barriers to industrial symbiosis, and to help develop solutions to overcome those barriers.
- Scholars who focus more on issues of consumption could add this aspect to the more production-oriented focus of industrial symbiosis.
- The resource recovery community has obvious connections to industrial symbiosis, but lacks the focus on geographic-proximity. If its expertise can be leveraged, information exchange between the two groups could be mutually beneficial.
- The fact that economic motivations are so important for industrial symbiosis suggests that more economists would be a natural addition to these discussions. Especially for developing countries, grounding industrial symbiosis in the language and understanding of economic activities is key.

Conclusion

If industrial symbiosis is to be adopted more widely, information about how such systems work and their benefits and costs needs to be communicated to a broader community, including both the public, which can demand that such activities be a part of business practice, as well as the business and regulatory communities who have the power to change current practices to adopt this hypothetically more sustainable form of organization.

Reorganizing industrial activities with the environment in mind is a critical part of the path to sustainable development. Arguably, industrial symbiosis gives us a common base from which to consider how the relationships of industrial organisms can be mutually beneficial. Researchers in industrial symbiosis identified many key questions described here, as well as opportunities for transferring knowledge and tools from other fields. Many more inquiries, issues, and instruments can be added as these ideas circulate through the growing industrial symbiosis community.

APPENDIX A: INDUSTRIAL SYMBIOSIS RESEARCH SYMPOSIUM SCHEDULE

JANUARY 7-9, 2004

Wednesday – January 7, 2004

7:00 pm Dinner at Templeton's Restaurant at the New Haven Hotel, 229 George Street

Thursday – January 8, 2004

7:30 am Breakfast: served on the 7th floor of the New Haven Hotel

8:40 am Vans depart from New Haven Hotel for Yale School of Forestry & Environmental Studies, Sage Hall, 205 Prospect Street

9:00 am Symposium Welcome and Introductions: Bowers Auditorium, Sage Hall

9:30 am Opening Remarks: Marian Chertow, Yale University

10:00 am Regional Round-Ups
Discussion on the status of industrial symbiosis in:
- *Western Europe (David Gibbs and Arnulf Hasler)*
- *Asia-Pacific region (Jun Bi and Rene van Berkel)*
- *South Asia (Ramesh Ramaswamy)*
- *North America (Ray Côté and Judy Kincaid)*
- *Africa and Americas (Weslynne Ashton)*

11:00 am Cross-Cutting Themes – A Response to the Regional Round-Ups
Leo Baas, Erasmus University
Reid Lifset, Yale University
Ernie Lowe, Indigo Development

11:30 am Plenary Discussion
Moderator: Marian Chertow, Yale University

12:30 pm Lunch: Sage Hall Lounge

1:30 pm Focal Area Session IA: Bowers Auditorium, Sage Hall

Modeling

Assessment of explanatory and predictive tools that can be applied to industrial ecosystems

Moderator: Thomas Graedel, Yale University

Speakers:
Clint Andrews, Rutgers University – Agency Modeling
Matthew Realff, Georgia Institute of Technology – Process Modeling

2:30 pm Focal Area Session IB: Bowers Auditorium, Sage Hall

Planning

Industrial symbiosis in regional systems and institutional initiatives for implementation

Moderator: Stefan Anderberg, University of Copenhagen

Speakers:
Tsuyoshi Fujita, Toyo University – Systems Planning
Jouni Korhonen, University of Tampere – Regional Planning

3:00 pm – 15 minute break –

3:45 pm Break-Out Sessions
Two moderated discussion sessions on modeling and planning run simultaneously.

Modeling: Sage Room 32 with Tom Graedel

Planning: Sage Room 24 with Stefan Anderberg

5:15 pm Moderators' Reports - summarizing break-out session discussions

5:40 pm Vans depart Sage Hall for New Haven Hotel

6:45 pm Vans depart New Haven Hotel for Yale School of Management, 55 Hillhouse Avenue

7:00 pm Dinner: General Motors Room, Yale School of Management

Friday – January 9, 2004

7:30 am Breakfast: Served on the 7th floor of the New Haven Hotel

8:40am Vans depart for Sage Hall, 205 Prospect Street

9:00 am Focal Area Session IIA: Bowers Auditorium, Sage Hall

Multi-Scale Analysis

Dimensions of industrial ecosystems

Moderator: Helge Brattebø, Norwegian Technical University

Speakers:
Stephen Levine, Tufts University – Multi-Scale Ecological Analysis
Tom Graedel, Yale University – Multi-Scale In-Use Copper Flows

10:00 am Focal Area Session IIB: Bowers Auditorium, Sage Hall

Economics and Business Strategy

Industrial symbiosis in current economic thought

Moderator: John Ehrenfeld, International Society for Industrial Ecology

Speakers:
Noel Jacobsen and Jørgen Christensen, Symbiosis Institute, Kalundborg – Contractual Relationships in Kalundborg

Rachel Lombardi, Yale University – Business Case for Symbiosis: Guayama, Puerto Rico

11:00 am – 15 minute break –

11:15 am Break-Out Sessions
Two moderated discussion sessions on multi-scale analysis and economics and business strategy run simultaneously.

Multi-Scale: Sage Room 32 with Helge Brattebø

Economics: Sage Room 24 with John Ehrenfeld

12:45 pm Moderators' Report: summarizing break-out session discussions

1:00 pm Lunch: Sage Lounge

2:00 pm Small Group Discussions
A: Bowers Auditorium with Jose Colucci, University of Puerto Rico
B: Sage Lounge with Sam Ratick, Clark University
C: Sage Room 24 with Reid Lifset, Yale University
D: Sage Room 32 with Ong, Boon Lay, National University of Singapore

3:00 pm – 20 minute break used to prepare group responses –

3:20 pm Responses to Small Group Questions

3:45 pm Plenary Discussion
Moderator: John Ehrenfeld, International Society for Industrial Ecology

4:30 pm Long-Term Vision and Next Steps
Moderator: Marian Chertow, Yale University

5:15 pm Closing

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APPENDIX C: RECENT PUBLICATIONS BY SYMPOSIUM PARTICIPANTS

Andrews, Clinton J. Building a Micro Foundation for Industrial Ecology. *Journal of Industrial Ecology*. 2001. Vol. 4. No. 3. pp. 35-51.

Andrews, Clinton J. Industrial Ecology and Spacial Planning. Chapter in *A Handbook of Industrial Ecology*, Robert and Leslie Ayres, eds. Cheltenham, U.K.: Edward Elgar, 2002.

Axtell, Robert L., Clinton J. Andrews, and Mitchell J. Small. Agent Based Modeling and Industrial Ecology. *Journal of Industrial Ecology*. 2002. Vol. 5, No. 4. pp.10-13.

Baas, L.W. and F.A. Boons. An Industrial Ecology Project in Practice: Exploring the Boundaries of Decision-making Levels in Regional Industrial Systems. *Journal of Cleaner Production*, forthcoming 2004.

Chertow, Marian. Industrial Symbiosis: Literature and Taxonomy. *Annual Review of Energy and Environment*, Vol. 25, 2000.

Côté, Raymond P. and E. Cohen-Rosenthal. Designing Eco-Industrial Parks: A Synthesis of Some Experiences. *Journal of Cleaner Production*, 1998. 6 (181-188).

Deschenes, PJ and Marian Chertow. An Island Approach to Industrial Ecology: Towards Sustainability in the Island Context. *Journal of Environmental Planning and Management*. In press, 2004.

Desrochers, Pierre. Cities and Industrial Symbiosis: Some Historical Perspectives and Policy Implications. *Journal of Industrial Ecology*. 2002: Volume 5, Number 4.

Ehrenfeld, John and Marian Chertow. Industrial Symbiosis: the Legacy of Kalundborg. Chapter in *A Handbook of Industrial Ecology*, Robert and Leslie Ayres, eds. Cheltenham, U.K.: Edward Elgar, 2002.

Forward, Gordon and Andrew Mangan. By-Product Synergy. *The Bridge*. Vol. 29, No. 1, Spring 1999.

Geng, Yong and Raymond P. Côté. Scavengers and Decomposers in an Eco-Industrial Park. *International Journal of Sustainable Development and World Ecology*. 2002. 9: 333-340.

Gibbs, David. Trust and Networking in Inter-firm Relations: The Case of Eco-Industrial Development. *Local Economy*, forthcoming, 2004.

Hardy, Catherine and Thomas E. Graedel. Industrial Ecosystems as Food Webs. *Journal of Industrial Ecology*. 2002. Vol. 6, No. 1. pp. 29-38.

Kincaid, Judy and Michael Overcash. Industrial Ecosystem Development at the Metropolitan Level. *Journal of Industrial Ecology*. Vol. 5, Issue 1- Winter 2001. 17-126.

Korhonen, Jouni. Four Ecosystem Principles for an Industrial Ecosystem. *Journal of Cleaner Production*. 2001. 9: 253-259.

Korhonen, Jouni. Two Paths to Industrial Ecology: Applying the Product-based and Geographical Approaches. *Journal of Environmental Planning and Management*. 2002. 45(1), 39-57.

Jacobsen, N.B. and S. Anderberg. “Understanding the Evolution of Industrial Symbiotic Networks – The Case of Kalundborg” ISIE Conference: The Science and Culture of Industrial Ecology. Leiden: 12-14 Nov 2001.

Milchrahm, Elisabeth and Arnulf Hasler. Knowledge Transfer in Recycling Networks: Fostering Sustainable Development, 2002.

Mirata, Murat. Experiences from Early Stages of a National Industrial Symbiosis Programme in the UK: Determinants and Coordination Challenges. *Journal of Cleaner Production*, forthcoming, 2004.

Ozyurt, D.B. and M.J. Realff, “Combining a Geographical Information System and Process Engineering to Design an Agricultural-Industrial Ecosystem,” in *Journal of Industrial Ecology*, 2001. Volume 5, Number 3, pp. 13-31.

Schwarz, Erich J. and Arnulf Hasler. Recycling Networks in Denmark and Upper Styria. 2000.

Van Beers, Dick and T.E. Graedel. The Magnitude and Spatial Distribution of In-use Copper Stocks in Cape Town, South Africa. *South African Journal of Science* 99. January/February 2003: 61-69.

Zhu, Qinghua and Ernest Lowe. Integrated Chain Management for Green Marketing and Regional Sustainable Development: A Case Study of China, *pre-publication copy*.

APPENDIX D: ADDITIONAL INDUSTRIAL SYMBIOSIS RESOURCES AND PUBLICATIONS SUBMITTED BY SYMPOSIUM PARTICIPANTS

Resources

Chertow, Marian and Michelle Portlock, eds. *Developing Industrial Ecosystems: Approaches, Cases, and Tools*. Yale School of Forestry & Environmental Studies. 2002. Bulletin Number 106. http://www.yale.edu/environment/publications/

Côté, Raymond P. A Primer on Industrial Ecosystems: A Strategy for Sustainable Industrial Development. http://www.mgmt.dal.ca/sres/pdfs/PRIMER.pdf. 2000.

Journal of Industrial Ecology. http://mitpress.mit.edu/JIE

Lowe, Ernest. Eco-Industrial Handbook for Developing Countries in Asia. Prepared under a grant from the Asian Development Bank Environmental Department. 2001. http://www.Indigodev.com/ADBHBdownloads.html

Pilot Project Plan for Development of a Recycling Economy in Liaoning Province, Translation of an official planning document by the Liaoning Provincial Government Circular Economy Office

National Industrial Symbiosis Programme. http://firstsupply.co.uk/nisp/

Stanford University, Graduate School of Business, Applied Sustainability LLC: Making a Business Case for By-Product Synergy, Case Number: E-118, Feb 2002.

The Symbiosis Institute. Industrial Development Council. Kalundborg, Denmark. http://www.symbiosis.dk.

University of Hull, Geography Department, Eco-Industrial Development www.hull.ac.uk/geog/research/EcoInd

United States Business Council on Sustainable Development By-Product Synergy Project. http://usbcsd.org/byproductsynergy.htm

U.S. Department of Energy, Texas Technology Showcase, and Texas Industries of the Future. By-Product Synergy Supports Sustainable Development.

Websites related to Australian industrial symbiosis case studies:
Gladstone, Queensland: http://www.sustainablegladstone.com/by_products.htm
Kwinana, Western Australia: http://www.kic.org.au/sustainability.html

Publications

Ammons, J.C., M.J. Realff, and D. Newton, "Decision Models for Reverse Production System Design," in *Handbook of Environmentally Conscious Manufacturing*, ed. C.N. Madu, Kluwer: Boston, 2001.

Andrews, C. J. Putting Industrial Ecology into Place: Evolving Roles for Planners, *Journal of the American Planning Association*, 1999. 65, pp. 364-375.

Andrews, C. J. Overcoming the Open System Problem in Local Industrial Ecological Analysis. *Journal of Environmental Planning and Management*, 2001. 44: 491-508

Chertow, Marian. Industrial Symbiosis. In *Encyclopedia of Energy*. Cutler J. Cleveland, ed. Elsevier. In press, 2004.

Cohen-Rosenthal, Edward, ed. with Judy Musnikow. *Eco-industrial Strategies – Unleashing Synergy between Economic Development and the Environment*. Sheffield, UK: Greenleaf Publishing 2003.

Côté, Raymond P. and Steven Peck. Beyond Waste Management: Transforming the Mind-Set. Presented at The Canadian Waste Management Conference. 2000.

Erkman, Suren and Ramesh Ramaswamy. Applied Industrial Ecology – A New Platform for Planning Sustainable Societies. Bangalore, India: Aicra Publishers 2003.

Lambert, A. and F. Boons. Eco-Industrial Parks: Stimulating Sustainable Development in Mixed Industrial Parks. *Technovation* 2002. 22: 471-484.

Lifset, Reid and Thomas E. Graedel. "Industrial Ecology: Goals and Definitions" from *A Handbook of Industrial Ecology* Robert and Leslie Ayres, eds. Cheltenham, U.K.: Edward Elgar, 2002.

Ozyurt, D.B. and M.J. Realff, "Combining Geographic Information Systems Process and Environmental Modeling for Macro-Level Pollution Prevention," in *Process Design Tools for the Environment*, eds. S.K. Sikdar and M.M. El-Halwagi, Philadelphia: Taylor & Francis Publishing, 2001, pp. 341-369.

The Center for Industrial Ecology at Yale

The Center for Industrial Ecology (CIE) was established in September 1998 to provide an organizational focus for research in industrial ecology. The Center brings together Yale faculty and staff, students, visiting scholars, and practitioners to develop new knowledge at the forefront of the field. Research is carried out in collaboration with other segments of the Yale community, with other academic institutions, and with international partners in Austria, China, The Netherlands, Switzerland, and elsewhere. Among the programs and goals of the Center are:

- Research in industrial ecology
- Hosting of visiting national and international scholars in industrial ecology
- Doctoral and postdoctoral study programs in industrial ecology

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