Sustainable Development through Industrial Ecology

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Sustainable development has emerged as a powerful force that is reshaping the policies and practices of global manufacturing firms. The principle of sustainability states that as we strive for economic prosperity and growth, we must not compromise the quality of life for our descendants. For corporations, seeking sustainability involves designing environmentally and socially responsible technologies, products, and processes with a full awareness of their life cycle costs and benefits. The concept of industrial ecology (IE) provides a useful systems perspective to support sustainable development while assuring shareholder value creation. IE is a broad, holistic framework for guiding the transformation of industrial systems from a linear model to a closed-loop model that resembles the cyclical flows of ecosystems. In particular, the field of green chemistry represents an important set of design strategies for achieving the goals of IE through fundamental innovations.

Emergence of the Sustainable Development Concept

The original concept of "sustainable development" (SD) set forth a vision of industrial progress that respects both human needs and global ecosystems, assuring the quality of life for future generations. The underlying principle was first introduced by the Bruntland Commission in 1987, which defined SD as:

...industrial progress that meets the needs of the present without compromising the ability of future generations to meet their own needs

- World Commission on Environment & Development (1)

There are a number of pervasive issues associated with SD that present severe challenges to the continued growth of global industries, particularly in developing nations. According to the World Bank (2), these include:

- Potential climate change due to CO_2 and other global warming gases
- Degradation of air, water, and land in industrialized areas
- Depletion of natural resources, including fresh water, biomass, and minerals
- Loss of agricultural land due to deforestation and soil erosion
- Threatened wildlife habitats, including forests, reefs, and wetlands

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- Lack of potable water for approximately 1.5 billion people
- Unsanitary urban conditions (over 2 billion people lack access to sewers)
- Proliferation of both viral and bacterial infectious diseases
- Increasing resource needs due to population growth (~90 million/year)
- Social disintegration resulting from displacement of traditional lifestyles
- Growing income gaps between rich and poor strata of society
- Lack of primary education for about 130 million children worldwide
- Extreme poverty (about 3 billion people, or roughly half the world's population, are estimated to earn under $2/day)

For the most part, these problems are neither speculative nor localized. Collectively, they represent the greatest threat that human society has ever faced, easily dwarfing public health concerns over environmental carcinogens in industrialized parts of the world. Historically, most of these issues appeared remote from the comfortable perspective of the more affluent nations. Today, thanks to the revolution in modern telecommunications, the globalization of markets, and the rapid growth of developing economies, SD issues cannot be so easily ignored.

A landmark event that raised the international visibility of SD was the Earth Summit of 1992, held in Rio de Janeiro, officially known as the United Nations Conference on Environment and Development. The issues discussed there transcended national and industrial boundaries, ranging from the export of pollution to developing nations to the international equity of environmental regulations and the sustainability of population and industrial growth in the face of limited planetary resources (3). In addition to the SD principle above, a number of key principles were articulated at the Rio Summit, including:

- The "precautionary approach" i.e., where there are threats of serious or irreversible damage, scientific uncertainty shall not be used to postpone cost-effective measures to prevent environmental degradation.
- The notion that environmental protection should constitute an integral part of the development process and cannot be considered in isolation from it.
- The "polluter pays" concept, i.e., polluters should bear the cost of pollution.

There is now increasing support around the world for public policy measures to promote SD, including not only regulatory requirements, but also establishment of waste reduction targets, promotion of "cleaner" production methods, and government support for research and development into environmentally sound technologies in order to stimulate the practice of SD.

The Response of Industry

The threat of government decision-makers assigning pollution taxes to selected industrial sectors was certainly a forceful "wake-up call" to the business community. For example, the United Kingdom recently enacted an energy tax (known as the Climate Change Levy) which penalizes industrial firms if they do not achieve certain levels of energy efficiency. However, apart from any government mandates or incentives, there has been a quiet revolution in industry attitudes toward the SD issues raised in Rio. A significant factor in this revolution was the creation of the World Business Council for Sustainable Development (WBCSD), a Geneva-based consortium of over 100 leading companies formed in 1990 to develop a global perspective on SD. Their book, *Changing Course*, is an important manifesto describing the both the challenges and the opportunities for profitability associated with corporate sustainability (4). Subsequently, WBCSD has published a series of studies that demonstrate the business value of sustainability and is coordinating the definition of agendas for change in industries such as pulp and paper, mining, cement, transportation, and electric power.

SD is arguably a logical outgrowth of evolving industry practices, including environmental stewardship, pollution prevention, waste minimization, and design for environment methods, which seek to replace "end-of-pipe" pollution control with more cost-effective process improvements. However, there are two important differences that distinguish SD from historical environmental management practices:

- Introduction of the socio-economic dimension, focusing upon the beneficial or adverse impacts of industrial growth upon societal well-being.
- Recognition of the linkages between SD and competitive advantage in the marketplace, which elevates these issues to a strategic level.

Confronted by rising stakeholder concerns, the business community has recognized that long-term success depends not only on financial performance, but also on social and environmental performance. Today, we define a "sustainable business" as one that is able to anticipate and meet the needs of present *and future* generations of customers and stakeholders, encompassing three dimensions of need known as the "triple bottom line":

- Economic prosperity and continuity for the business and its stakeholders
- Social well-being and equity for both employees and affected communities
- Environmental protection and resource conservation, both local and global

From this perspective, corporate sustainability is not just altruism – rather, it is an enlightened response to emerging market forces. Instead of merely listening to the voice of the individual customer, companies are beginning to listen to the collective voice of the larger Customer; namely, human society. Public awareness of sustainability creates opportunities for companies to address changing stakeholder expectations with new technologies, products, and services, thus gaining competitive advantage (5).

Sustainable Business Practices

In recent years, a number of leading multinational corporations have established highly visible sustainability programs. For example, top management at BP Amoco, Dow, DuPont, Ford, General Motors, Royal Dutch Shell, and IBM have gone public with ambitious commitments to generate shareholder returns while addressing the needs of humanity. In general, the common purpose of these programs is to shift the company operations from a traditional, resource-intensive, and profit-maximizing business model to a more eco-efficient, socially responsible, and value-maximizing model. This shift aligns nicely with the financial goal of increasing shareholder value by raising profits while reducing the cost of capital – i.e., doing more with less.

Early adopters of SD have included companies in many different industries, such as chemicals, consumer products, pharmaceuticals, motor vehicles, computers and electronics, forest products, petroleum, and even floor-coverings. Rather than following a prescribed approach, each company has explored how it can integrate sustainability into its own business strategy. For example, DuPont has adopted a company-wide sustainability indicator (shareholder value added per pound of product) that reflects their overall goal of creating greater value with fewer resources – i.e., doing more with less. In contrast, Procter & Gamble (P&G) is building its sustainability efforts around two focused themes:

- Water – since 85% of its products involve household water use, P&G is investigating how to enhance both water conservation and water quality.
- Health & hygiene – P&G is seeking to enhance the global contributions of its products to sanitation, health care, infant care, and education.

Typically, there are several levels of sustainable business practices, with increasing levels of difficulty. The most basic level is corporate initiatives such as philanthropic programs aimed at solving sustainability problems. The next level often involves reducing the "ecological footprint" associated with the product life cycle, including manufacturing, use, and end-of-life disposition. The most challenging level is enhancing the *inherent social value* created by the firm's operations, products and services, which may range from assuring human health and nutrition to stimulating consumer education and growth of new businesses. At this level, challenging trade-offs may arise – for example, balancing job creation and economic development against community concerns about industrial pollution and environmental justice.

One of the greatest pitfalls of SD is viewing it as a regulatory compliance issue, and addressing it through typical environmental, health and safety programs. Companies that are successful SD practitioners typically view SD as a strategic issue, have the Chief Executive Officer or other senior executives as champions, and encourage cross-functional collaboration throughout the organization in pursuit of innovative products and business models. For example, product designers compare the sustainability profiles of competing product concepts, marketers analyze how to differentiate their product or service in terms of life cycle cost of ownership, production managers apply environmental accounting to quantify hidden environmental costs, and strategic planners assess the consequences of long-term SD scenarios. Finally, most practitioners agree that for SD to become truly integrated into business decisions, a systematic SD performance measurement process is essential.

Four fundamental principles can help companies address the challenges associated with measuring and reporting product sustainability (6). These are:

- Address the dual perspectives of *resource* consumption and *value* creation.
- Include economic, environmental, and societal aspects.
- Systematically consider impacts associated with each stage in the product life cycle, including resource extraction, procurement, transportation, manufacturing, product use, service, and disposition.
- Develop both *leading* indicators to measure internal process improvements and *lagging* indicators to measure external results.

Most companies that are committed to SD have established measurable performance goals and have expanded their annual environmental, health and safety progress reports into sustainability reports aimed at stakeholder communication. Tools such as life cycle assessment are increasingly used to measure performance in terms of total societal impacts. Meanwhile, emerging consensus standards such as the Global Reporting Initiative (7) are helping to establish key performance indicators that will support industry benchmarking. Examples of commonly used SD indicators are shown in Table 1.

Table 1. Examples of Sustainability Indicators

Economic	*Environmental*	*Societal*
Direct • Raw material costs • Labor costs • Capital costs • Operating costs	**Material Consumption** • Product & packaging mass • Useful product lifetime • Hazardous materials used	**Quality of Life** • Breadth of product availability • Knowledge enhancement • Employee satisfaction
Potentially Hidden • Recycling revenue • Product disposition cost	**Energy Consumption** • Life cycle energy • Power use in operation	**Peace of Mind** • Perceived risk • Complaints
Contingent • Employee injury cost • Customer warranty cost	**Local Impacts** • Product recyclability • Impact upon streams	**Illness & Disease Reduction** • Illnesses avoided • Mortality reduction
Relationship • Loss of goodwill due to customer concerns • Business interruption due to stakeholder interventions	**Regional Impacts** • Smog creation • Acid rain precursors • Biodiversity reduction	**Accident & Injury Reduction** • Lost-time injuries • Reportable releases • Number of incidents
Externalities • Ecosystem productivity loss • Resource depletion	**Global Impacts** • CO_2 emissions • Ozone depletion	**Health & Wellness** • Nutritional value provided • Food costs

Industrial Ecology as a Normative Framework

One of the most significant barriers to sustainable development is the broad scope and complexity of the issues that need to be addressed, ranging from minimization of ecological impacts associated with industrial waste streams to enhancement of quality of life in developing nations. It is difficult for decision-making teams to anticipate the multitude of cause and effect chains that drive the ultimate beneficial or adverse impacts of their proposed investments or technical innovations. Instead, they need to adopt fundamental *design principles* that are "normative" in the sense that they will generally lead to positive outcomes, although one can never guarantee the absence of hidden drawbacks.

As shown in Figure 1, during the late 20th century, there was a rapid evolution in normative approaches used by industry managers for integrating environmental and social considerations into business decision-making.

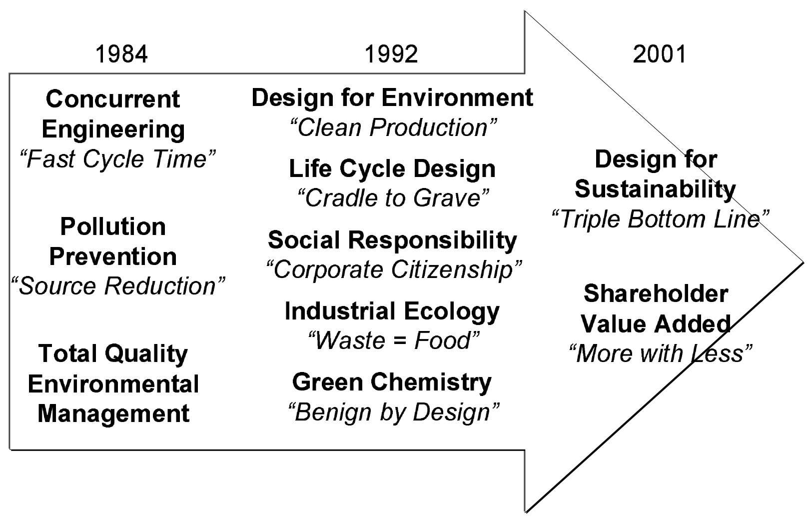

Figure 1: Evolution of Industry Approaches to Sustainable Development

The convergence of accelerated product development methods (such as concurrent engineering) with pollution prevention thinking led to the widespread adoption of approaches such as Design for Environment, which provides systematic guidelines for anticipating and enhancing the environmental performance of new products and processes. This was accompanied by the development of analytical approaches for evaluating performance at both a product and system level, most notably the body of methods known as *life cycle assessment*. An early foundation for industrial ecology was Robert Ayres' work on industrial metabolism, which examined the life-cycle patterns of energy and materials in an industrial system (8). These inter-related threads of thought have evolved into what now are the two dominant themes of sustainable business – designing sustainable systems and creating shareholder value.

In the above context, industrial ecology (IE) is a relatively new discipline that offers design principles to support both business innovation and evaluation of sustainability performance. Stated simply, industrial ecology is *a broad, holistic framework for guiding the transformation of industrial systems from a linear model to a closed-loop model* that resembles the cyclical flows of ecosystems. In nature, there is no waste – one creature's waste becomes another creature's food. Thus, IE provides a foundation for rethinking conventional product or process technologies and discovering innovative pathways for re-use and recovery of industrial waste streams. However, it should be noted that industrial ecology focuses mainly on the ecological and economic dimensions of sustainability. A comparable paradigm that supports societal sustainability considerations has not yet been developed.

There are as many alternative definitions of industrial ecology as there are authors promoting the concept. Here are some examples:

> *"Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources."*
>
> *—Robert M. White, President,*
> *US National Academy of Engineering (9)*

> *"Industrial ecology . . . is a systems view of industrial operations in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to waste product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital."*
>
> *—David Chiddick, Vice President, AT&T (10)*

> *"Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process."*
>
> *—Hardin Tibbs (11)*

> *[T]he ultimate goal . . . is bringing the industrial system as close as possible to being a closed-loop system, with near complete recycling of all materials.*
>
> *—Ernest Lowe (12)*

All of these definitions share some basic assumptions, namely that industrial systems must function within natural constraints, that ecosystem principles offer guidance in the design and management of industrial systems, and that optimization of material and energy flows will generate both environmental and economic benefits

One influential group that has stimulated the introduction of IE thinking into major corporations is the Natural Step (13), a Sweden-based organization that advocates four required "system conditions" for achieving sustainability:

- Avoid increases in substances extracted from the Earth's crust.
- Avoid increases in non-degradable substances produced by society.
- Avoid displacement, over-harvesting, or other ecosystem manipulation.
- Use resources fairly and efficiently in order to meet human needs globally (this is considered an imperative for achieving the first three conditions).

While these conditions are challenging to meet in the absolute sense, they are consistent with the general principles of IE articulated above.

Cyclical Flows in Industrial Systems

At the heart of industrial ecology is the notion of emulating natural systems by seeking cyclical industrial flows, which some have called "biomimicry"14. The traditional, linear model of industrial economics assumes that raw materials are acquired at the beginning of the value chain and are then processed and incorporated into intermediate and final products, which are in turn delivered to product users or consumers, who use the products and discard or recycle them. Wastes that are generated along this chain are "exported" outside the system for appropriate disposition. The notion of *eco-efficiency*, in its simplest form, focuses on the manufacturing stage of the value chain and seeks to generate higher-value outputs with reduced resource inputs (see Figure 2).

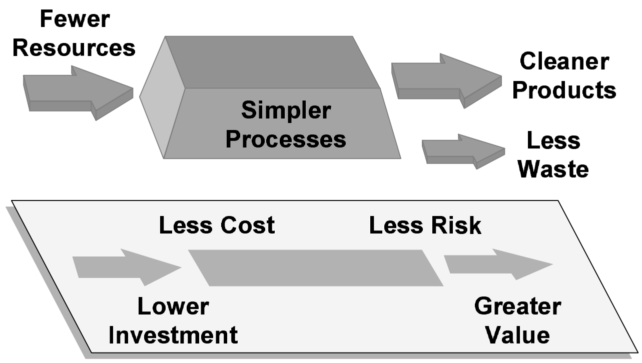

Figure 2: Benefits of increasing eco-efficiency for a manufacturing activity

In contrast, the cyclical model approaches industrial activities from a systems perspective and seeks to optimize overall efficiency, ultimately eliminating all waste. This concept is illustrated in Figure 3, which shows several different types of pathways for waste utilization, including:

- Closed-loop recovery (recycling of feedstock process waste)
- Conversion of process waste to byproduct (from Product A to Product B)
- Recycling of post-consumer waste (from Product A consumption)
- Waste to energy conversion (Product A post-industrial and post-consumer)

Each of the industrial ecology flows depicted in Figure 3 can potentially provide economic benefits to both the waste generator and the waste consumer.

An example of how industrial ecology concepts are currently applied in the consumer electronics industry, including personal computers and peripherals, is presented in Figure 4. Since technologies are improving so rapidly, product life cycles in this industry are extremely short, and a "reverse logistics" infrastructure has evolved to handle the large stream of obsolete hardware, recovering valuable components and in many cases refurbishing them for resale. The same overall system design could apply to most types of assembled durable goods, such as home appliances or automobiles.

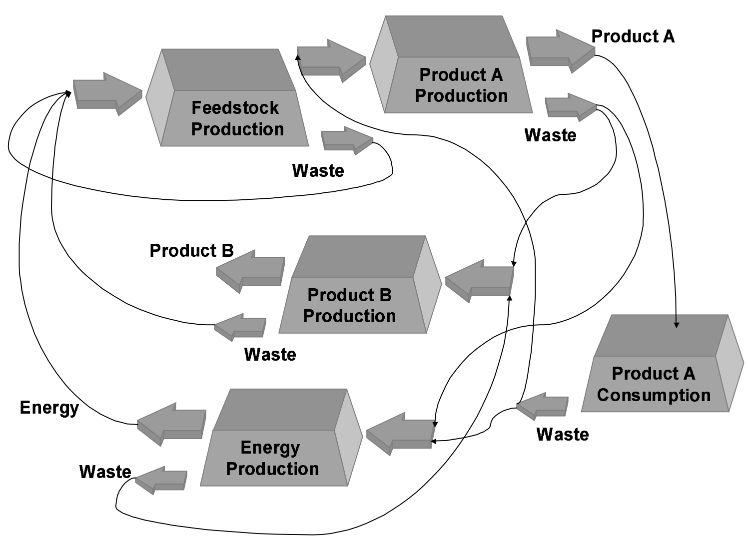

Figure 3: Examples of cyclical flows in an industrial ecosystem

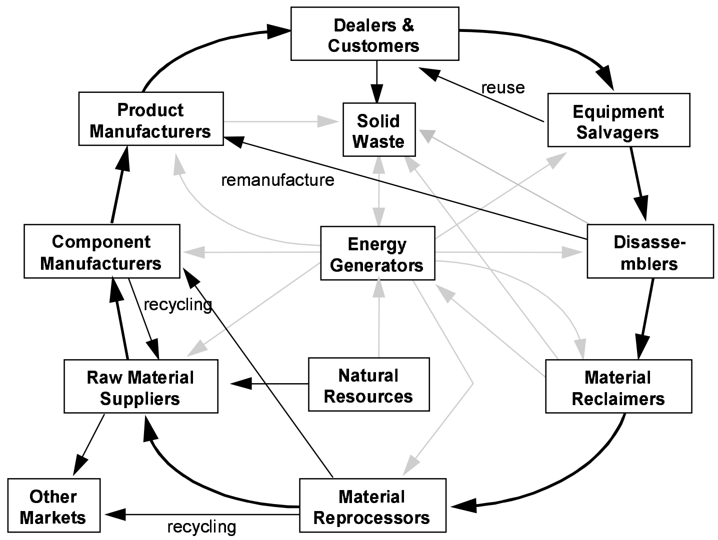

Figure 4: Industrial ecology model for consumer electronics

Extending these concepts, William McDonough and Michael Braungart, have given a particularly lucid and creative presentation of what they call an "eco-effective" system, one that eliminates waste by discovering benign or even restorative flows of materials and energy (15). This concept is illustrated in Figure 5. Any waste products from the product supply chain are converted into either biological nutrients (i.e., returned to the earth) or technical nutrients (i.e., recycled into the same or other product value chains).

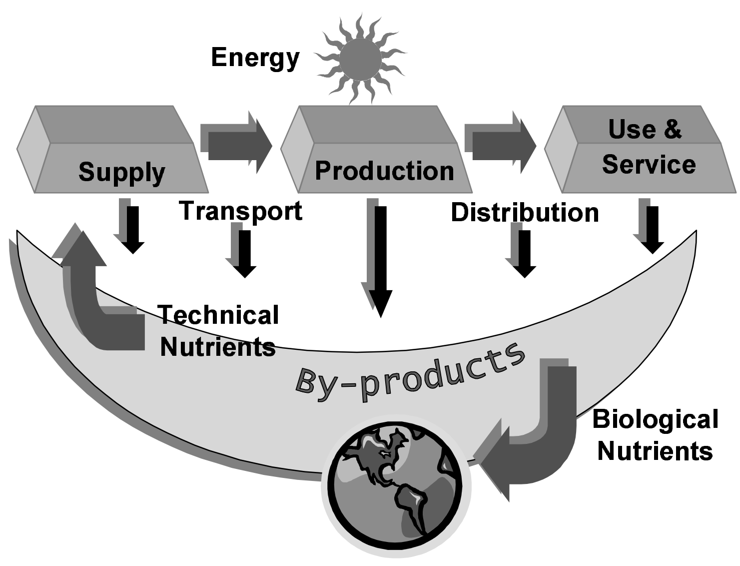

Figure 5: Flows of materials and energy in the biosphere

Industrial Ecology in Practice

A much publicized example of IE in practice is the industrial complex at Kalundborg, Denmark, where "symbiotic" relationships have developed among several large manufacturing facilities and a host of smaller ones (16). The main partners are a coal-fired power plant, a refinery, a plasterboard factory, and a pharmaceutical and enzyme plant operated by Novo Nordisk. IE flows include capture of waste heat for municipal uses and aquaculture, emission recovery (e.g., fly ash, sulfur) for substitute fuel and raw materials, and agricultural applications of waste streams. These relationships developed spontaneously based on economic incentives, but despite much effort at designing "eco-industrial parks," comparable examples are scarce.

The major impact of IE thinking has been to provide a fundamental design logic that guides awareness of environmental and social considerations in both the creative phase and the evaluative phase of new product or process development. Many companies have made efforts to systematize IE principles in the form of design guidelines. For example, companies as diverse as 3M, Caterpillar, AT&T, Johnson and Johnson, and Bristol-Myers Squibb have developed Product Life Cycle Management programs that include Design for Environment (DfE) or Design for Sustainability guidelines. These programs include both review and enhancement of existing products and modification of the new product realization process to incorporate sustainability considerations.

The influence of IE thinking is also evident in recent actions of the U.S. Federal government. For example, the Environmentally Preferable Purchasing guidelines published by the U.S. Environmental Protection Agency specify products and materials that are considered environmentally friendly due to their recyclability, use of recycled content, and energy efficiency. Similarly, Executive Order 13123, *"Greening the Government Through Efficient Energy Management,"* has directed Federal agencies to apply the principles of Sustainable Design and Development to the siting, design and construction of new facilities, and also directs agencies to optimize life-cycle costs, pollution, and other environmental and energy costs associated with the construction, life-cycle operation and decommissioning of facilities.

There are numerous examples in various industries of companies that have realized financial and competitive advantages through the use of IE strategies. The efforts of leading chemical companies such as Dow and DuPont to develop sustainable products and reduce their environmental footprints are well documented. Even in industries with a more traditional image, IE has shown great promise. The following are outstanding examples:

- Chapparal Steel in Midlothian, Texas, has developed a steel mill based on industrial ecology concepts. They formed new company to recycle electric arc furnace slag into cement production, reducing energy use and CO_2 emissions, and they constructed a world-class shredding and recycling facility adjacent to the plant. To enable these innovations, they acquired an exclusive separation technology for non-chlorinated plastics and are participating in byproduct synergy exploration with other firms (17).
- Collins & Aikman Floorcoverings in Dalton, Georgia, has been a pioneer in the use of innovative, sustainable technologies. They developed an adhesive-free carpet installation system, with 100% closed-loop recycled backing. As a result of product and manufacturing innovations, between 1993 and 1997 they were able to achieve a 68% increase in production volume, a 78% reduction in waste per square yard, 43% lower energy use, and 41% lower water use.

Green Chemistry as an Industrial Ecology Strategy

Green Chemistry, also known as "sustainable chemistry," is a particular branch of DfE that is concerned with environmentally benign chemical synthesis and processing. It differs from conventional DfE efforts in that DfE tends to focus on the mechanical design of products or packaging, resulting in incremental improvements for discrete products, (e.g., an inkjet printer or a bottle of shampoo). In contrast, Green Chemistry focuses on fundamental breakthroughs in product or process chemistry, deals with properties of materials at the molecular level, and therefore has the potential to discover more radical and more powerful solutions with greater beneficial impacts.

Green Chemistry research can develop innovative ways to address many of the goals associated with IE. Examples include:

- Reducing material intensity through the use of alternative chemistries that have higher "atom efficiency."
- Reducing energy intensity through lowering the energy requirements of endothermic reactions, e.g., by using novel catalysis methods.
- Reducing the dispersion of toxic substances through discovery of "benign synthesis" pathways, or through elimination of organic solvents.
- Enhancing material recyclability by developing biodegradable materials or finding methods to regenerate feedstocks from waste byproducts.
- Enhancing process yield and reducing waste by developing more effective separation and extraction methods, enabling byproduct recovery.
- Improving the durability and performance of products by developing novel materials or multi-layered composites with customized physical properties.
- Maximizing the sustainable use of renewable resources by developing bio-based processing methods for converting biomass (e.g., soybeans, corn, cellulose) into useful materials.
- Developing innovative products that are environmentally-benign (e.g., Rohm and Haas developed an eco-friendly marine anti-foulant).

As an example of green chemistry innovations, researchers at Battelle Memorial Institute have been developing economically attractive polymer products based on renewable feedstock derived from plant sources such as soybeans. Advances in plant genomics and genetic engineering have opened practical ways to build chemical functionality into proteins and oils typically found in plant seeds, offering new paths for developing commercially viable products. This research program has resulted in the following developments:

- An environmentally compatible, soybean oil-derived plasticizer for use in the processing of polyvinyl chloride resin, in order to replace phthalate, benzoate and other petroleum-derived products.
- A soy-based wood adhesive that performs better than current adhesives, is less costly, and will reduce emissions of volatile organic compounds.
- A novel, readily de-inkable toner technology based on soy resins, addressing a growing need in the manufacture of secondary fiber from office waste.
- Lactide polymer production from fermentation processes, for use in manufacture of biodegradable polymers.
- A cost effective "green" solvent, consisting of a water based, biodegradable micro-emulsion, that uses the excellent solvent characteristics of methyl ester of soybean oil.

While much of green chemistry is focused upon the development of new chemical pathways, there is also an important, related field of DfE in the area of green chemical engineering. The main focus of this field is to improve the economic and environmental performance of industrial processes through optimization of process design and operating conditions. Figure 6 illustrates a heuristic design strategy based on a tree-structured logic, which can be used to reduce byproduct formation in continuous reaction processes (18).

Conclusions

The newfound emphasis on sustainable development within the business community signals an emerging synthesis between traditional business values and the concepts of environmental and social responsibility. Practically, speaking, as global environmental and economic pressures intensify, the need for sustainability awareness will become a business imperative. The world population has surpassed six billion, while concerns about climate, water, land, and habitat preservation continue to mount. Rapidly developing economies around the world are creating growing markets for goods and services. These conditions are generating opportunities for companies to fundamentally change how they engage suppliers, operate facilities, and service customers.

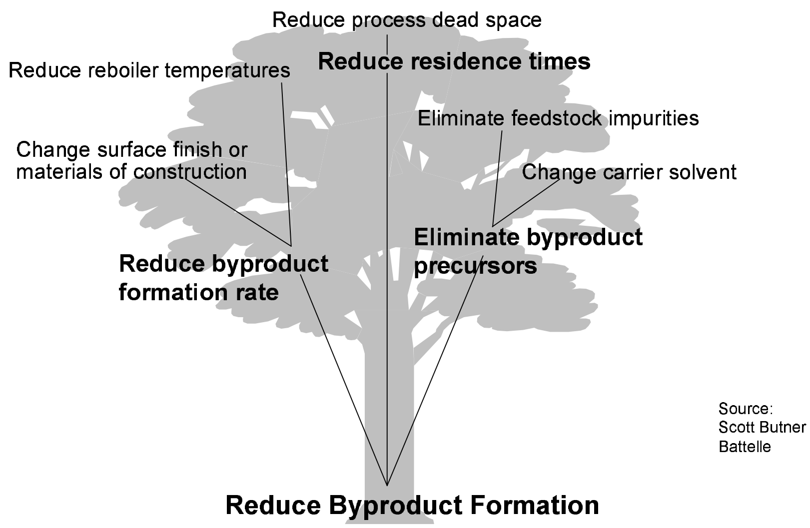

Figure 6: Heuristic Process Design Rules

In addition to new technologies, new production methods, and new management systems, companies that adopt SD will need a new, holistic paradigm to support creative research and innovation. Industrial ecology offers such a paradigm, at least for the environmental and economic aspects of sustainability. Specifically, green chemistry focuses on fundamental changes in material properties and process chemistries that can enable radical reductions in resource consumption and waste generation while creating economic value across the supply chain. The next logical challenge, as yet unaddressed, is to develop a unifying conceptual paradigm that encompasses not only the environmental and economic aspects, but also the social aspects of sustainable development – a common framework for both natural and human capital.

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