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Strategies for Manufacturing[1]

Waste from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment

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People create new technologies and industries to meet human needs more effectively and at lower cost. Innovation is a major agent of progress, and yet innovators' incomplete knowledge sometimes leads to undesirable side effects. Such unforeseen consequences of new inventions are not unique to the feverish industrialization of the 19th and 20th centuries. The ancient Greek myths tell of Pandora and the box full of plagues, of Prometheus punished for stealing fire from the gods and of Icarus, who plummeted from the sky when the sun's heat melted the wax of his wings. In historical times the shift from rawhide to tanned leather, although it made for garments and tools that lasted much longer and were more comfortable to wear and use, brought stenches and disease, so that tanneries had to be segregated from the communities they served.

Today such inadvertent effects can have a global impact. Consider, for example, the invention of chlorinated fluorocarbons. Before CFC's were developed in the 1930's, refrigerator compressors contained ammonia or sulfur dioxide; either chemical was toxic, and leaks killed or injured many people. CFC's saved lives, saved money and provided such elements of modern life as air-conditioned buildings and untainted food. Only later did atmospheric scientists determine that CFC's contribute to global warming and affect the chemistry of the upper atmosphere, where they destroy ozone.

Such failures should not diminish the fact that technology has improved the lot of people everywhere. Standards of living in many parts of the world are better today than they were 20 or 30 years ago. Many of the adverse effects of industrialization have been brought under control by further applications of technology. Yet as the world's population and standard of living increase, some of the old solutions to industrial pollution and everyday wastes no longer work. There is often no "other side of town" where the modern equivalents of tanneries can be put, no open space beyond the village gates where garbage can be dumped and do no harm.

By the year 2030, 10 billion people are likely to live on this planet; ideally, all would enjoy standards of living equivalent to those of industrial democracies such as the U.S. or Japan. If they consume critical natural resources such as copper, cobalt, molybdenum, nickel and petroleum at current U.S. rates, and if new resources are not discovered or substitutes developed, such an ideal would last a decade or less. On the waste side of the ledger, at current U.S. rates 10 billion people would generate 400 billion tons of solid waste every year enough to bury greater Los Angeles 100 meters deep.

These calculations are not meant to be forecasts of a grim future. Instead they emphasize the incentives for recycling, conservation and a switch to alternative materials. They lead to the recognition that the traditional model of industrial activity in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of should be transformed into a more integrated model: an industrial ecosystem. In such a system the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products serve as the raw material for another process.

The industrial ecosystem would function as an analogue of biological ecosystems. (Plants synthesize nutrients that feed herbivores, which in turn feed a chain of carnivores whose wastes and bodies eventually feed further generations of plants.) An ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living and the developing nations are to raise theirs to a similar level without adversely affecting the environment.

If both industrialized and developing nations embrace changes, it will be possible to develop a more closed industrial ecosystem, one that is more sustainable in the face of decreasing supplies of raw materials and increasing problems of waste and pollution. Industrialized nations will have to make major and minor changes in their current practices.

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[1] The original title proposed by the authors was **"Manufacturing -- The Industrial Ecosystem View",** but was not accepted!

Developing nations will have to leapfrog older, less ecologically sound technologies and adopt new methods more compatible with the ecosystem approach.

Materials in an ideal industrial ecosystem are not depleted any more than those in a biological one are; a chunk of steel could potentially show up one year in a tin can, the next year in an automobile and 10 years later in the skeleton of a building. Manufacturing processes in an industrial ecosystem simply transform circulating stocks of materials from one shape to another; the circulating stock decreases when some material is unavoidably lost, and it increases to meet the needs of a growing population. Such recycling still requires the expenditure of energy and the unavoidable generation of wastes and harmful by-products, but at much lower levels than are typical today.

Today’s industrial operations do not form an ideal industrial eco-system, and many subsystems and processes are less than perfect. Yet there are developments that could be cause for optimism. Some manufacturers are already making use of "designed offal," or "engineered scrap," in the manufacture of metals and some plastics: tailoring the production of waste from a manufacturing process so that the waste can be fed directly back into that process or into a related one. Other manufacturers are designing packaging to incorporate recycled materials wherever possible or are finding innovative uses for materials that were formerly considered wastes.

Three examples delineate some of the issues involved in developing self-sustaining industrial process systems: the conversion of petroleum derivatives to plastics, the conversion of iron ore to steel, and the refining and use of platinum-group metals as catalysts. We have picked these examples because each represents a different stage in the evolution of a closed cycle. Examining their workings and shortcomings should provide insight into how subsystems can be improved so as to develop an industrial ecosystem.

The iron cycle, in which recycling is well established, is a very mature process with a history dating back thousands of years, even though extensive production of steel did not begin until the 19th century. The plastics cycle, in which reuse is just beginning to make its mark, is less than 100 years old; the first completely synthetic plastic, Bakelite, was introduced shortly after the turn of the century. The platinum group metals cycle in which reuse is common because of the high cost of the materials involved is even younger: industrial noble metal catalysts became widely used only in the early 1950’s, and the widespread use of noble metals to reduce pollution from automotive exhaust dates back less than 15 years.

The plastics system is potentially highly efficient, but realizing that potential poses challenges that have yet to be met. Plastics are a diverse group of chemically complex compounds whose use has grown explosively, so that they now present a growing disposal problem. Plastics are formed into any number of products, and different plastic resins are difficult to distinguish. This difficulty leads to problems in collection, separation and recycling. Moreover, breaking plastics down to their original chemical constituents is often technologically infeasible or economically unattractive.

The drawbacks of plastics must nonetheless be weighed against their benefits. Plastic containers, for example, are safer than the glass containers they replace. Countless injuries, from minor cuts to severe lacerations, have been prevented by the substitution of plastic for glass in milk bottles and containers for bathroom products such as shampoo. Plastic containers are generally lighter than glass or metal ones, so that less energy is required to transport them; they also require less energy to make than glass or metal containers, especially if they are recycled. The Midwest Research Institute in Kansas City, Mo., determined that compared with glass containers, half-gallon polyvinyl chloride (PVC) containers require less than half the energy to produce and transport and consume one-twentieth the mass of raw materials and less than one-third as much water in their manufacture. They also generate less than half of the waste of glass manufacturing.

Each kind of plastic poses different problems depending on its particular composition and use. PVC, of which almost four million tons are produced every year in the U.S., is a particularly dramatic example of the complex threats plastics pose to the environment. PVC, which accounts for about one-sixth of total plastic production, is made into products ranging from pipes to automobile parts to shampoo bottles. Its production requires both hydrocarbons and chlorine. (The chlorine makes the plastic’s impact on the environment greater than it would be if only hydrocarbons were required as is the case for polyethylene, for example.) Natural gas is the most commonly used feedstock for PVC in the U.S.; elsewhere it is naphtha, a petroleum fraction. In either case the feedstock is converted to ethylene, which is chlorinated to form vinyl chloride monomer; the monomer molecules are then linked to form PVC.

The efficiency of the production process has already been improved. For example, manufacturers have developed more efficient membrane cells for the electrolysis of sodium chloride to produce the required chlorine. (The sodium chloride, common table salt, is dissolved in cells through which a current flows; sodium ions migrate to one electrode, and chlorine ions migrate to the other. A membrane separates the two electrodes.) The membrane cells also eliminate the asbestos and mercury required in older electrolysis cells, thus reducing hazardous wastes.

Even so, the PVC production process exemplifies classic "end of pipe" control measures for reducing pollutants. Emissions of vinyl chloride monomer during manufacturing are tightly controlled, a practice instituted when it became known that the monomer is both toxic and carcinogenic. Unreacted vinyl chloride is generally stripped from the finished PVC by low-pressure steam. Most of the monomer is recovered and recycled, but some of it is present at concentrations too low for easy recovery and recycling; instead it is sent to an incinerator to be broken down. Scrubbers remove hydrochloric acid from the exhaust.

Recycling of PVC during manufacturing is fairly straightforward. Plants that make PVC products typically recycle almost all of their in-house scrap. At General Motors, for example, scrap generated in the manufacture of PVC parts such as decorative trim, seat covers and dashboards is segregated by color, reground, melted and used along with virgin PVC.

Once plastic enters the consumer market, however, recycling becomes considerably more complicated. Only about 1 percent of the PVC discarded by consumers is recycled. The wide range of products in which PVC is found makes collection and recovery more difficult, but it also creates interesting opportunities. For example, potential health hazards and liability concerns prevent recycled plastics from being incorporated into containers where the plastic touches food; recycled bottles may find their way into drainage pipes instead.

Other vinyl products that cannot easily be recycled can be burned to produce heat or electricity. PVC contains roughly as much energy as wood or paper, but its chlorine content poses problems: incinerators that burn PVC must have scrubbers to prevent emissions of hydrochloric acid, which contribute to acid rain. During combustion the chlorine can also form small amounts of dioxins, which are believed to be potent carcinogens. As a result, the incineration of discarded PVC is discouraged. Although recent tests by the New York State Energy Research and Development Authority have shown that properly designed and operated incinerators do not emit significant quantities of hydrochloric acid or dioxins, environmentalists and regulators are not convinced that incinerators would achieve such low emission levels in practice.

Because of its chlorine content, PVC is a worst-case example of the problems plastics pose. Other polymers such as polypropylene and polyethylene present fewer environmental hazards. They have physical properties similar to those of PVC, but they contain no chlorine. Polyethylene terephthalate (PET), the material used in carbonated beverage bottles, is recycled in nine states that have mandatory deposit laws: California, Connecticut, Delaware, Maine, Massachusetts, Michigan, New York, Oregon and Vermont. Bottles collected in these states account for 150 million of the 750 million pounds of PET resin produced every year. Recyclers pay from $100 to $140 per ton of PET, making it the second most valuable component of municipal solid waste after aluminum. The PET is reconstituted into resins for injection molding to produce products ranging from automobile parts to electronic devices or is spun into polyester fibers that go into pillows, stuffed furniture, insulated clothing and carpeting.

As the infrastructure for collecting and sorting PET and other consumer plastics grows, recycling rates should increase significantly. According to recyclers such as Wellman Inc., of Shrewsbury, N.J., which currently processes about 100 million pounds of PET a year, the market for recycled plastics is limited by collection efficiency rather than by demand.

The industrial system for iron presents a different picture. Techniques for recycling are well established, and there is a strong infrastructure for collecting scrap. Yet discarded metal continues to pile up in scrapyards and across the U.S. because there is not enough demand for it. Elemental iron, the predominant component of both steel and cast iron, is the backbone of modern life: it is used in roads, in the automobiles that pass over the roads and in buildings. In the U.S. iron production begins when ore is mined in huge open pits as deep as 100 meters or more. The ore is concentrated and formed into pellets at the mine and then converted into pig iron in a blast furnace, where it is heated with coke, limestone and air. The coke adds carbon to the mix, and the limestone and the oxygen in the air react with impurities in the ore to form slag, which is then removed. Small admixtures of other elements yield steel to be cast, rolled or forged into billets, slabs, beams or sheets.

Once iron has been formed into products, which are eventually discarded, its properties (especially its ferromagnetism) facilitate identification and separation. The enormous amount of iron in circulation makes recycling relatively easy and economically attractive. It is not surprising, therefore, that every year millions of tons of scrap join iron ore to produce steel products. The scrap generated by stamping steel parts for automobiles, for example, is recycled into engine blocks and other castings. All four foundries that GM operates rely entirely on scrap steel obtained from other GM operations and on scrap iron generated during the casting process.

Although iron recycling is a relatively simple process, the system is not a closed loop. Much of the scrap from discarded consumer products is not recovered but is scattered around the countryside, where it corrodes away a little every year and is considered a blight rather than an asset. In 1982 recoverable iron scrap amounted to 610 million tons; at the end of 1987, the figure had risen to more than 750 million. A major reason for the increase is that U.S. production of iron and steel during this period was the lowest it had been since the end of World War II. The demand for scrap to make steel decreased while iron and steel products continued to be scrapped at the previous rate.

Shifting patterns of steel manufacturing, both in the U.S. and around the globe, are responsible for the increase in scrap. One subtle culprit is a technology shift from open-hearth furnaces to basic oxygen furnaces for producing steel. Basic oxygen furnaces (so called because they make steel in a large closed vessel supplied with pressurized oxygen) require only 25 tons of scrap steel to be mixed with every 100 tons of pig iron from the blast furnace, as opposed to a nearly equal mix for the open hearth.

The shift to basic oxygen furnaces began in the U.S. about 1958, and today open-hearth furnaces account for less than 3 percent of total production. Open-hearth furnaces were replaced to improve manufacturing efficiency and reduce air pollution, but their disappearance led to a decline in iron recycling. In making these changes, steel makers had no economic mechanism for taking account of the adverse environmental impacts of scrap accumulation or the possible long-term effects of consuming more iron ore for each unit of steel.

More recently minimills have been built that rely on electricarc furnaces and consume scrap steel almost exclusively. These low-volume mills have increased their share of U.S. steel production, but not enough to compensate for the lost demand for scrap to feed open-hearth furnaces. Furthermore, minimills produce only a limited range of steel products, and many of those products must be made from scrap containing very low levels of impurities. Scrap that contains excess copper, for example, is not suitable for making sheet steel, because the resulting sheet is too brittle to form into products. If electric-arc furnaces are to make significant inroads into the U.S. stock of scrap iron, they must be coupled to production facilities that produce a wider range of products, and better techniques must be developed for dealing with impure scrap.

Platinum group metals (platinum, palladium, rhodium, ruthenium, iridium and osmium) were, until the mid-1970's, part of a very efficient industrial system. These metals were once recycled with efficiencies of 85 percent or better, but the advent of catalytic converters for automobiles dealt this system a shock from which recycling rates are only now beginning to recover.

Recycling of platinum-group metals is dictated not so much by the environmental effects of their disposal as by their limited supply and the difficulties of mining and refining them. Ores contain only about seven parts per million of mixed platinum-group metals, so that about 20 million metric tons a year must be refined to produce 143 tons of purified metals—an amount that could fit into a cube roughly two meters on a side.

About 60 percent of the platinum-group metals mined is formed into metal products such as jewelry, ingots for investors and chemical reaction vessels; these products are eventually recycled with almost complete efficiency. The remainder is used to make chemicals and catalysts for chemical plants, petroleum refineries and automobiles. Catalysts adsorb molecules on their surfaces and promote chemical reactions that either join the molecules together or break them into smaller ones. Catalytic converters for automobiles, which reduce exhaust emissions of hydrocarbons, carbon monoxide and oxides of nitrogen, are the most rapidly growing use of platinum-group metals; consumption rose from about 11.5 metric tons in 1975 to about 40 in 1988. Automobiles currently account for most of the yearly permanent consumption of platinum-group metals.

Platinum-group metals in industrial applications are recycled quite efficiently. Each plant uses large amounts of catalyst, so that the payoffs from recycling are clear. Used catalysts are generally recycled every few months, providing a large, continuing stream of materials for reclaimers to process. In chemical and pharmaceutical plants, for example, catalysts are typically recycled in less than a year, and about 85 percent of the platinum-group metals in them are recovered. Some petroleum refineries are even more successful, recovering up to 97 percent of their noble metals.

The automotive pattern of noble metal use stands in sharp contrast to that of the process industries: there are tens of millions of catalytic converters, each of which contains only a few grams of platinum-group metals (less than two grams of platinum, for example), and the lifespan of about 10 years for an average car makes for a much slower turnover of recyclable materials. As a result, only about 12 percent of the platinum group metals in catalytic converters is currently recycled.

Poor recycling rates for automotive catalysts can be blamed almost entirely on the lack of an effective means for collecting discarded converters. The technology for recovering platinum group metals from the converters is quite well understood; a plant opened by Texasgulf Minerals & Metals, Inc., in Ala. in 1984 recovers 90 percent of the platinum, 90 percent of the palladium and 80 percent of the rhodium from used converters. Millions of individual converters, however, are dispersed among thousands of scrapyards and almost 2,000 automotive scrap recyclers. The cost of locating, collecting and emptying the converters and then transporting the catalyst to a reprocessing plant is sufficiently high so that recycling is not profitable for most refining operations unless the price of platinum exceeds $500 an ounce.

The outlook for catalytic converter recycling is improving. Now that most of the first generation of cars built with catalytic converters have found their way to U.S. scrapyards, there is a large, continuing flow of raw materials for recyclers. More important, an infrastructure for collecting spent converters is being established. Even Japanese companies such as Nippon Engelhard have set up collecting organizations in the U.S. to acquire automotive catalysts for reprocessing in Japan. In addition the introduction of more stringent emissions controls in Europe, where catalytic converters have not been required, will increase the demand for platinum group metals, making recycling more profitable.

The life cycles of plastics, iron and the platinum group metals illustrate some of the issues involved in creating sustainable industrial systems. Equally important is the way in which the inputs and outputs of individual processes are linked within the overall industrial ecosystem. This linkage is crucial for building a closed or nearly closed system.

Like their biological counterparts, individual manufacturing processes in an effective industrial ecosystem contribute to the optimal function of the entire system. Processes are required that minimize the generation of unrecyclable wastes (including waste heat) as well as minimize the permanent consumption of scarce material and energy resources. Individual manufacturing processes cannot be considered in isolation. A process that produces relatively large quantities of waste that can be used in another process may be preferable to one that produces smaller amounts of waste for which there is no use.

A good example of the subtleties involved is the dematerialization of manufactured goods the use of plastics, composites and high strength alloys to reduce the mass of products. The trend toward dematerialization has drawn increasing attention in recent years. The mass of a typical automobile, for example, has decreased by more than 400 kilograms since 1975; about 100 kilograms of the decrease are due to the substitution of aluminum and plastics for steel. Lighter cars burn less gasoline. Steel, however, is easy to recycle, whereas the composite plastics that have replaced it resist reuse. The net result may be an immediate drop in fuel consumption but an overall increase in the amount of permanent waste created and in the resources consumed.

Waste minimization activities in U.S. industries have been aided by regulations developed in the late 1970's to control hazardous waste disposal. The regulations, reflecting long term environmental costs, have increased the cost of landfill disposal from less than $20 a ton to $200 a ton or more, making alternatives to disposal profitable. Many companies find it profitable to sell their wastes as raw materials. For example, Meridian National in Ohio, a midwestern steel processing company, reprocesses the sulfuric acid with which it removes scale from steel sheets and slabs, reuses the acid and sells ferrous sulfate compounds to magnetic tape manufacturers.

If the production of unrecyclable wastes is to be eliminated, similar steps must be taken for each of the low-level by-products in large streams of process effluents. Although emissions at each stage of such manufacturing processes may be relatively small, taken together they can cause serious pollution problems. Minimizing each of these myriad smaller emissions one at a time is a complex and potentially costly challenge.

The challenge can be met in part by implementing a multitude of relatively small changes. Some chemical plants and oil refineries, for example, have significantly reduced their hazardous waste output by simply changing their procedures for buying and storing cleaning solutions and other low-volume chemicals. By doing so, they have been able to eliminate the need to dispose of leftover amounts.

At ARCO's Los Angeles refinery complex, a series of relatively low-cost changes have reduced waste volumes from about 12,000 tons a year during the early 1980's to about 3,400 today, generating revenue and saving roughly $2 million a year in disposal costs. The company sells its spent alumina catalysts to Allied Chemical and its spent silica catalysts to cement makers. Previously these materials were classified as hazardous wastes and had to be disposed of in landfills at a cost of perhaps $300 a ton.

Alkaline carbonate sludge from a water-softening operation at the refinery goes to a sulfuric acid manufacturer a few miles away, where it neutralizes acidic wastewater. (The acid manufacturer previously purchased pure sodium hydroxide for the same purpose.) A few outflow pipes have been rerouted to improve access for loading, and plant personnel must track the pH of their sludge, but the total investment has been minimal.

The ARCO refinery has also started to recover oil from internal spills and other wastes in a new $1-million recycling facility. When the recycler is fully operational next year, it is expected to reduce wastes by another 2,000 tons. Off-site treatment or landfilling will still be needed for miscellaneous wastes such as solvents, spray cans and the several hundred tons of asbestos insulation being removed from the plant each year.

ARCO's situation is not unique; other major refiners and chemical manufacturers are engaged in similar efforts. For example, investments of $300,000 in process changes and recovery equipment at Ciba-Geigy's Toms River plant in New Jersey reduced disposal costs by more than $1.8 million between 1985 and 1988. Dow Chemical established a separate unit to recover excess hydrochloric acid, which it then either recycles to acid-using processes or sells on the open market. The operation recovers a million tons of acid a year at a profit of $20 million.

By-products and effluents created during manufacturing represent only the supply side of the industrial ecosystem. The demand side is the consumer, who takes in manufactured goods and produces scrap that could be the raw materials for the next cycle of production. If the industrial ecosystem approach is to become widespread, changes in manufacturing must be matched by changes in consumers' demand patterns and in the treatment of materials once they have been purchased and used.

The behavior of consumers in the U.S. today constitutes an aberration in both time and space. Whereas a typical New Yorker, for example, discards nearly two kilograms of solid waste every day, a resident of Hamburg or Rome throws out only about half that as New Yorkers did at the turn of the century. Moreover, U.S. consumer habits and waste-management practices form a complex pattern that hinders efforts to reduce waste generation and the growing pressure on municipal landfills. The vast bulk of consumer wastes consists of organic materials and plastics that could relatively easily be composted, recycled or burned to produce energy but instead are stored in landfills, for which land was readily available in the past and where costs were low.

Today, as landfills across the U.S. near capacity, many communities have initiated garbage-sorting programs to reduce the amount of unrecycled waste; more initiatives are likely to follow. Some other countries have already instituted fairly sophisticated collection and treatment practices that go well beyond standard sorting and recycling. Japan, Sweden and Switzerland, for example, have set up collection centers for batteries from portable radios and other consumer products. The batteries contain heavy metals that render composted wastes unsuitable for fertilizing crops; the metals also contaminate fly and bottom ash from incinerators, so that the ash must be disposed of as hazardous waste.

An effective infrastructure for collecting and segregating various consumer wastes can dramatically improve the efficiency of the industrial ecosystem. The American consumer may have to stop heedlessly generating huge volumes of unsorted wastes, but living standards in the U.S. as a whole will not be affected. Moreover, landfills for municipal wastes are running out of space as rapidly as are those for industrial waste; consumers will soon find themselves facing the same economic incentives for waste reduction that producers face today.

Creating a sustainable industrial ecosystem is highly desirable from an environmental perspective and in some cases is highly profitable as well. Nonetheless, there are a number of barriers to its successful implementation. Corporate and public attitudes must change to favor the ecosystem approach, and government regulations must become more flexible so as not to unduly hinder recycling and other strategies for waste minimization.

Federal hazardous-waste regulations are a case in point. They sometimes make waste minimization more difficult than waste disposal. Because of the strict requirements for handling and documenting the treatment of wastes classified as hazardous, many companies choose to buy their materials through conventional channels rather than involve themselves in the regulatory process. A few states do encourage innovative treatment of wastes: California, for example, publishes a biannual catalogue that attempts to match waste generators with waste buyers manufacturers who need the materials they produce. About half a million tons of hazardous wastes that would otherwise have gone to landfills were recycled in 1987. A dozen other state, provincial and regional waste exchanges operate throughout the U.S. and Canada.

In addition to promoting innovative waste-minimization schemes, governments need to focus on the economic incentives for sustainable manufacturing. Increased landfill costs have forced companies to improve industrial processes and reduce unrecyclable waste, but many small emissions are still controlled by classic end-of-pipe regulations that specify how much of each pollutant may be discharged. Companies must meet regulatory requirements, but there are no direct advantages for manufacturers who capture and treat low-level effluents or who shift to production processes with more benign by-products. Conventional economic methods take into account only the immediate effects of production decisions. If a manufacturer produces nonrecyclable containers, for example, taxpayers at large bear the increased landfill costs; if a power plant reduces emissions that cause acid rain, communities elsewhere are likely to reap the benefits. Returns to the manufacturer or utility are generally indirect.

Instead of absolute rules, economists have long advocated financial incentives to reduce pollution. These include investment or research credits, tax relief, or fees or taxes imposed on manufacturers according to the amount and nature of the hazardous materials they produce. Such measures can help pay for treatment or disposal; more important, they give companies an incentive to change their manufacturing processes so as to reduce hazardous waste production. Fees and taxes for pollution make environmental costs internal, so that they can be taken into account when making production decisions.

Pollution fees have come under fire from environmentalists and industrialists as "licenses to pollute" and as "distortions of the market." Both criticisms are potentially valid. Companies can treat fees that are too low as a cost of doing business and pass them on to customers; fees that are too high may force companies to reduce emissions of specific pollutants without regard to other environmental effects or to financial burdens.

Suitably set charges or incentives, however, can be an effective means for manufacturers to incorporate societal costs of pollution and waste into their cost accounting systems. As in the case of rising landfill fees for hazardous wastes, cost feedback for other pollutants could make it more attractive to solve problems at the source rather than to destroy or dispose of effluents once they have been created. Such fees enable manufacturers to share in the overall economic savings accruing from reduced levels of hazardous materials. Providing economic incentives would harness manufacturers' strong competitive drive to reduce costs. Indeed, manufacturers who ignore this imperative perish from the marketplace, a situation that would not change if the societal costs of pollution were allocated to them.

Economic incentives alone are not enough to make the industrial ecosystem approach commonplace. Traditional manufacturing processes are designed to maximize the immediate benefits to the manufacturer and the consumer of individual products in the economy rather than to the economy as a whole. A holistic approach will be required if the proper balance between narrowly defined economic benefits and environmental needs is to be achieved. (Broadly defined, of course, economic and environmental goals are the same: bad places to live do not make for good markets.)

The concepts of industrial ecology and system optimization must be taught more widely. Current engineering and technological education either omit these concepts entirely or reach them in such a limited way that they have little impact on the approaches taken to the environmental problems associated with manufacturing. Changing the content of technological education, however, will not be enough. The concepts of industrial ecology must be recognized and valued by public officials, industry leaders and the media. They must be instilled into the social ethos and adopted by government as well as industry.

Government regulation of emissions at the local, national and international level will continue to play a strong role in the transition from traditional methods of manufacturing to an industrial ecosystem approach. The transition to an ecosystem approach would be accelerated by the early adoption of economic incentives as part of the regulatory system.

To make regulation as effective as possible, officials must base their policies on sound technology and make allowance for technological change. Rules must be cast so as to encourage (or at least not discourage) the development of alternative processes and innovative methods for dealing with industrial by-products. Regulators must take advantage of industry’s technological know-how so as to avoid counterproductive control measures. Such a wise regulatory framework will be almost impossible to construct unless government, industry and environmental groups abandon their current adversarial relationships and work together to solve their shared problems.

Even with an industrial ecosystem approach in place, decisions about how best to allocate resources will not always be easy. Petroleum, for example, is not just a source of energy but also a raw material essential for manufacturing chemicals, plastics and other materials. Some analysts have argued that it should be used only as a raw material and not for energy. A similar argument could be made for using coal as a feedstock instead of as a fuel. On the output side, plastics can be burned for energy, recycled into new products or even reduced to their chemical constituents; it is not clear which choice is unequivocally sounder. Careful analysis of the consequences by "industrial ecologists" will be required to answer such questions.

The ideal ecosystem, in which the use of energy and materials is optimized, wastes and pollution are minimized and there is an economically viable role for every product of a manufacturing process, will not be attained soon. Current technology is often inadequate to the task, and some of the knowledge needed to define the problems fully is lacking. The difficulties in implementing an industrial ecosystem are daunting, especially given the complexities involved in harmonizing the desires of global industrial development with the needs of environmental safety.

Nonetheless, we are optimistic. The incentive for industry is clear: companies will be able to minimize costs and stay competitive while adhering to a rational economic approach that accounts for global costs and benefits. Equally clear are the benefits to society at large: people will have a chance to raise their visible standards of living without incurring hidden environmental penalties that degrade the quality of life in the long run. Remembering that people and their technologies are a part of the natural world may make it possible to imitate the best workings of biological ecosystems and construct artificial ones that can be sustained over the long term.

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FURTHER READING

RESOURCE & ENVIRONMENTAL PROFILE ANALYSIS OF PLASTICS AND NONPLASTICS CONTAINERS. Robert G. Hunt and Richard O. Welch. Midwest Research Institute, 1974.

PLATINUM-GROUP METALS. J. Roger Loe-benstein in *Mineral Facts and Problems*, U.S. Bureau of Mines Bulletin No. 675, U.S. Department of the Interior. U.S. Government Printing Office, 1985.

THE MAKING, SHAPING, AND TREATING of STEEL. Edited by William T. Lankford, Jr., et al. Association of Iron and Steel Engineers, 1985.

TECHNOLOGY AND ENVIRONMENT. Edited by Jesse H. Ausubel and Hedy E. Sladovich. National Academy Press, 1989.

INPUT MANAGEMENT OF PRODUCTION SYSTEMS. Eugene P. Odum in *Science*, Vol. 243, No.4888, pages 177-182; January, 13, 1989.