

ENVIRONMENTALLY CONSCIOUS MANUFACTURING: A TECHNOLOGY FOR THE NINETIES

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Environmentally conscious manufacturing involves developing and implementing manufacturing processes that minimize or eliminate hazardous chemical waste, reduce scrap, or are operationally safer. The benefits include safer and cleaner factories, reduced future costs for disposal and worker protection, reduced environmental and health risks, improved product quality at lower cost, and higher productivity. Sandia and AT&T are committed to environmentally conscious manufacturing.

Introduction

In recent years, U. S. manufacturers have been subject to increasingly stringent environmental legislation. Federal, state, and local legislation currently regulate air emissions, water discharges, occupational exposure, and treatment and disposal of various hazardous chemicals. In addition, the Montreal Protocol, an international agreement signed by the U. S., regulates the production and use of halogenated organic compounds now known to deplete the Earth's ozone layer. In particular, chlorofluorocarbons (CFCs or Freons), some chlorinated hydrocarbons (CHCs) and halons are regulated. The 1990 Clean Air Act addresses urban air pollution, toxic emissions, and acid rain and emphasizes waste minimization as well as emission monitoring and reporting. The act lists 189 compounds for regulation as air toxics. Its regulations will have a serious impact on manufacturing.

Environmentally conscious manufacturing (ECM) goes beyond simple compliance with environmental regulations to drive a *philosophy* of pollution prevention. Sandia National Laboratories and AT&T are committed to improving the environment, and are actively researching ways to minimize or eliminate solid, liquid, and gaseous wastes. Included in our ECM programs are steps to decrease employee exposure to hazardous chemicals.

Increasingly stringent environmental regulations correlate directly with increased waste-associated costs. Waste disposal costs are increasing at an annual rate of ~10 percent. Often, stricter laws, new knowledge, or better chemical analyses redefine waste from non-hazardous to hazardous, resulting in a tenfold increase in disposal costs.

Panel 1. Acronyms in This Paper

BAT	best available technology
CFC	chlorofluorocarbons
CHC	chlorinated hydrocarbons
DFE	design for environment
DFX	<i>Design for X</i> , where X stands for downstream concerns such as manufacturability, testability, and installability
DOE	Department of Energy
ECM	environmentally conscious manufacturing
EPA	Environmental Protection Agency
FT-IR	Fourier transform—infrared spectroscopy
IPA	isopropyl alcohol
LSF	low solids flux
MDA	methylene dianiline
PWB	printed wiring board
T _c	critical temperature
TDI	toluene diisocyanate

24 Minimizing waste can reduce these costs. Optimizing processes and procedures to more efficiently use material will reduce production and disposal costs, because one frequent component of waste is material that is not used in the final product. For example, inventory practices can be optimized to ensure that a material with a short shelf life is used before its expiration date. Processes that are not optimized produce scrap and rework because the product doesn't meet quality specifications. The result in either example is increased materials and disposal costs.

Another component of manufacturing waste is *packaging material*. Supplies, components, and sub-assemblies come from suppliers packed in disposable material. Packaging material use should be limited to no more than is necessary to achieve the basic product protection function. Minimizing waste also will improve operating cost and energy efficiency. There are many hidden waste-associated costs, e.g., to track waste and hazardous materials, to obtain permits, to comply with the regulations, and to operate waste treatment facilities. Often, these costs are included in the operating overhead of a manufacturing plant, and are not identified with waste management. Waste reduction can often result in significant cost reduction.

Today's manufacturing process waste minimization will affect the company's future liability. It has become apparent that even well-regulated disposal can cause environmental damage. For example, as the detection limits

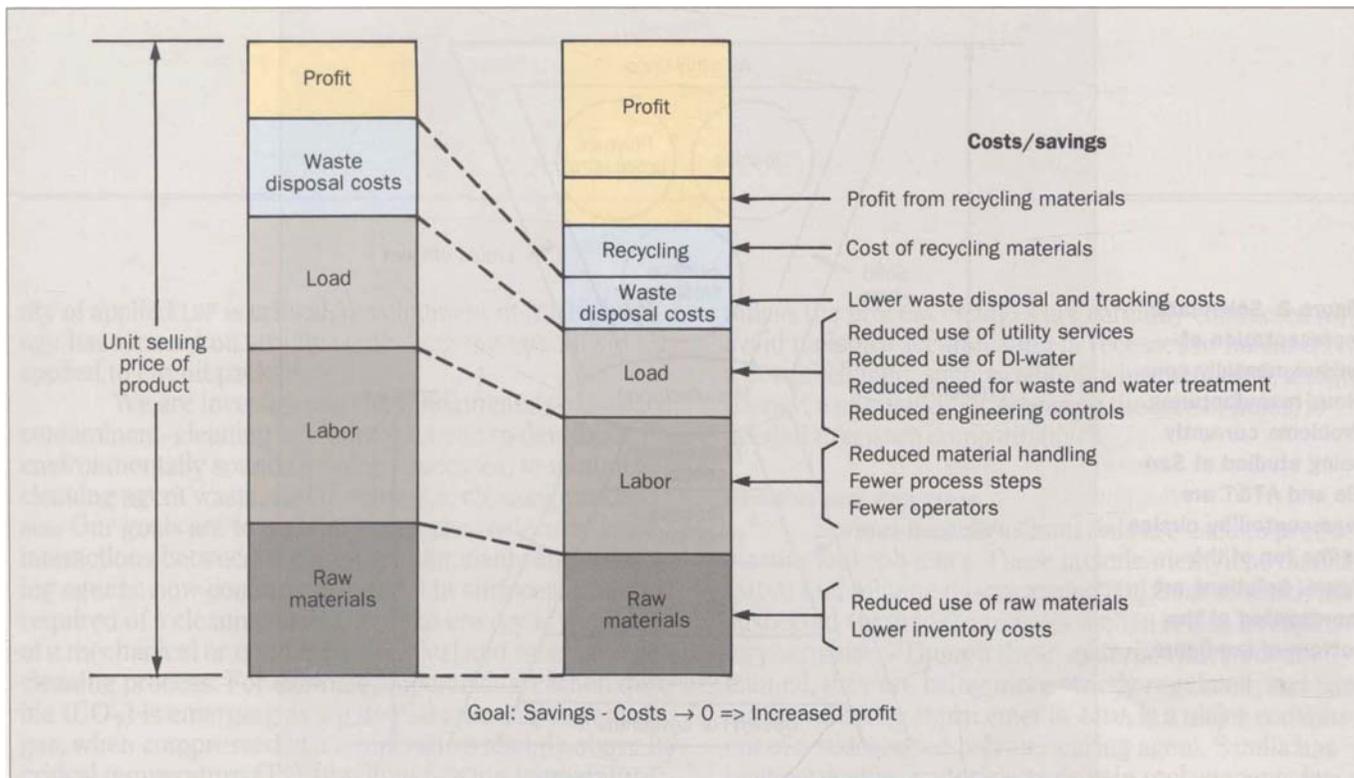
of chemical analyses have improved, lower pollutant levels can be detected, resulting in even stricter regulations. Many landfills, operated with what was considered the best available technology (BAT) for that time, have now become Superfund sites with the associated liability costs. (Superfund sites are hazardous waste sites especially designated by the EPA for cleanup.) Reducing generated wastes should result in reduced future liability costs associated with solid waste, air emissions, and liquid effluent.

The technology developed for ECM can have ancillary benefits for manufacturers. For example, operations that minimize the number of cleaning steps can improve productivity and quality. Decreasing hazardous chemicals emissions will improve public acceptance of manufacturing operations and enable manufacturers to be perceived as good neighbors. Sandia has an ongoing program to transfer its technology to U. S. companies, helping improve manufacturing productivity and the nation's international competitiveness at the same time it protects the environment.

Waste minimization makes both environmental and economic sense. Corporations are responsible for maximizing the investment of their shareholders. Therefore, it is incumbent on them to reduce operating costs (Figure 1). Waste minimization will lower today's disposal costs and reduce future potential liability costs. Corporations can gain marketing advantages by reducing waste. A national survey conducted by the Gallup organization indicated that about 90 percent of those surveyed would be willing to pay a premium for green products or packaging.¹

ECM Technology

The problems and solutions addressed by environmentally conscious manufacturing are depicted in Figure 2. ECM solutions that can be applied incrementally are shown as bars: the length of the bar represents the difficulty and time required for implementation. Those solutions that can be applied with current or advanced technologies are represented by diagonal supports.



Engineering controls, such as the addition of barriers to confine a hazardous chemical, can be used as a short-term ECM solution. Process modifications, such as decreasing the volume of cleaning solvents used, can also be used in the short term. Forward-looking, longer-term solutions include direct substitution of non-toxic for toxic materials, e.g., changing a cleaning solvent from trichloroethylene to isopropyl alcohol. Alternatively, a new process that omits hazardous chemicals can be used. For example, fluxless soldering eliminates the need for cleaning solvents to remove excess solder flux. A combination of ECM approaches is necessary for short- and long-term success in waste reduction.

The most forward-looking scenario goes as far as designing products to minimize waste during item production, use, and disposal. This approach is known as *Design for Environment* (DFE). Sandia and AT&T have many programs involving ECM. Representative examples from several areas are discussed in the following sections.

Cleaning/Solvent Substitution

Because cleanliness is a critical parameter in electronics manufacture, cleaning processes must insure

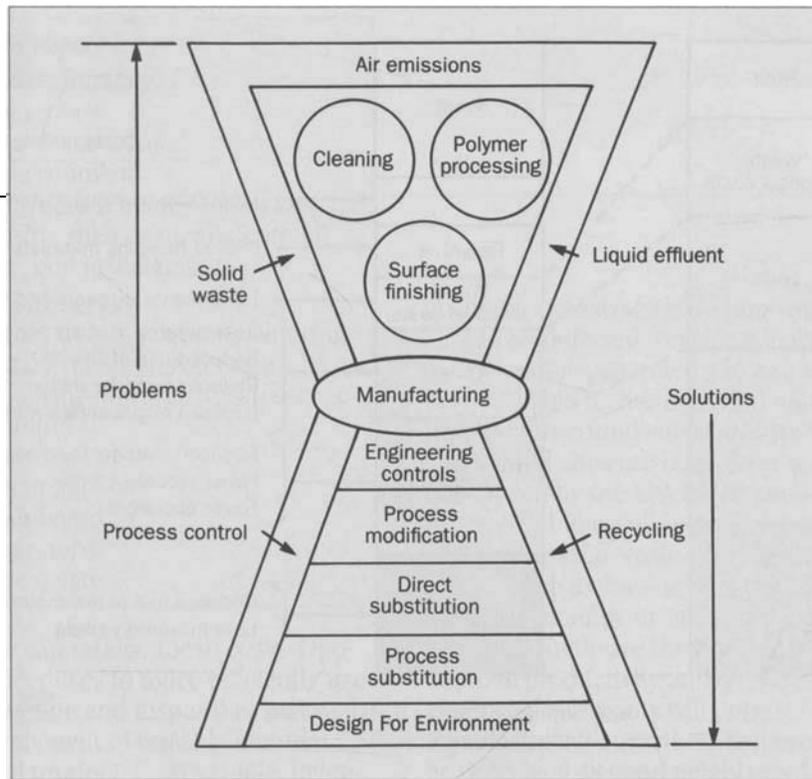
Figure 1. Economic benefit of waste minimization in manufacturing.

quality and functionality. However, they are non-value added processes that produce waste. It is important to eliminate or reduce as many of these manufacturing operations as possible. Sandia and AT&T both have active programs in minimizing cleaning waste.

Sandia is coordinating the Department of Energy's (DOE) effort to eliminate the use of halogenated solvents in cleaning. The program is being carried out jointly with the DOE production agencies. Traditionally, cleaning mechanical and electrical components has required halogenated solvents, particularly CFCs and CHCs. Sandia and AT&T have conducted tests to study the cleaning ability of non-halogenated, environmentally safe solvents. One Sandia study involved high-reliability printed wiring board (PWB) assemblies. PWBs require cleaning to remove process residues that can lead to corrosion, or degrade their electrical performance.

Four alternative commercially available cleaners were studied. The major active ingredient of each was: terpenes (naturally derived organic compounds),

Figure 2. Schematic representation of environmentally conscious manufacturing. Problems currently being studied at Sandia and AT&T are represented by circles at the top of the figure. Solutions are represented at the bottom of the figure.



N,N-dimethylacetamide, decyl acetate, and isopropyl alcohol (IPA). The first part of a 3-step program evaluated the cleaning efficiency of these solvents to remove oils, greases, and mold release agent from PWB coupons. (*Coupons* are test strips or pieces.) Weight loss data for soiled coupons showed the terpene-based and decyl acetate-based cleaners effectively remove the three contaminants. The dimethylacetamide cleaner and IPA were ineffective in removing the grease. A second step measured the fraction of a volatile radioactive compound (labeled-tetrabromoethane dissolved in cyclohexane) removed from a coupon. (*Labelling* indicates to researchers that a radioactive isotope has been incorporated into the compound.) This technique is effective to monitor the degree of surface cleanliness. Again, the terpene-based and the decyl acetate-based cleaners were effective cleaning agents, but the dimethylacetamide-based cleaner and IPA were not. A commercially available water-soluble hand cream was also used as a "stand-in" for body oils, and only the decyl acetate-based cleaner effectively removed these oils from test coupons. Overall, both the terpene- and the decyl acetate-based cleaners showed a broad range of cleaning capabilities. Because cleaning

equipment is commercially available for use with the terpene-based cleaner, and not for the decyl acetate-based cleaner, the former cleaning solvent was chosen to clean PWBs.

Another approach to eliminating halogenated solvents is to use a solventless cleaning process. One such process uses a hydrogen plasma for cleaning. Heavily oxidized copper surfaces can be cleaned effectively with hydrogen plasma (or hydrogen-argon) and subsequently soldered without fluxing. Hydrogen plasma reduces copper oxide more effectively than molecular hydrogen would.

Because cleaning is a non-value added process, the best solution is to eliminate it. AT&T and Sandia are pursuing this approach by developing Low Solids Flux (LSF) technology. LSF has a solids content in the range of 2 to 5 weight percent, compared to the usual 15 to 35 weight percent. LSF leaves little or no post-solder residue and eliminates the need for subsequent cleaning processes. It eliminates not only cleaning agent waste, but also cleaning machine capital, operating, and maintenance costs. It also reduces material costs. Because surface insulation resistance tests have shown that the quan-

tity of applied LSF is critical, development of LSF technology has focused on strictly controlling the quantity of LSF applied to circuit packs.²

We are investigating the fundamentals of surface contaminant-cleaning agent interactions to develop environmentally sound cleaning processes, to minimize cleaning agent waste, and to minimize cleaning processes. Our goals are to understand, at the molecular level, interactions between surfaces, contaminants and cleaning agents; how contaminants bond to surfaces; what is required of a cleaning agent, or what energy is required of a mechanical or combined chemical and mechanical cleaning process. For example, supercritical carbon dioxide (CO₂) is emerging as a potential cleaning solvent. A gas, when compressed at a temperature slightly above its critical temperature (T_c) (the liquefaction temperature), is converted to a supercritical state where it has singular properties. For example, a supercritical fluid is almost as dense as a liquid but retains gas-like properties such as low viscosity and high diffusivity. Supercritical CO₂ shows promise as a safe alternative to halocarbon cleaning solvents: it can dissolve many organic materials, especially organic species without hydrogen bonding capability. It is nontoxic, nonflammable, and environmentally safe. It contains neither hydrogen nor halogen, and will not corrode metal parts. It evaporates rapidly and does not leave any residues on the cleaning surface.

Problems with producibility, materials compatibility, and long term reliability may arise when replacing hazardous materials or processes with environmentally safer ones. These problems can be especially severe in enclosed systems or those designed for long lifetimes. In making any material or process change, it is important to consider the compatibility of a material—such as a cleaning solvent—with other materials it might contact, or which are in the vicinity. For example, halogenated solvents replaced aqueous-based solvents for cleaning because of corrosion problems associated with the latter. However, aqueous-based solvents are now replacing halogenated solvents. Corrosion problems may recur

unless the process changes are carefully conducted to avoid moisture accumulating in recesses or holes. Often a design change, such as adding a hermetic seal, another barrier, a scavenger, or changing the size of holes, is needed to ensure compatibility.

Plastics and Polymers

Several hazardous materials are used to produce plastics and polymers. These include methylene dianiline (MDA) and toluene diisocyanate (TDI), both of which are suspected (or listed) carcinogens; TDI is also a respiratory sensitizer. Though these materials have not been banned, they are being more strictly regulated, and Sandia is evaluating replacements. MDA is a major constituent of a widely-used polymer curing agent. Sandia has been evaluating materials as drop-in replacements for this curing agent. (*Drop-ins* can be substituted without any other process changes.) One is a commercially-available aromatic amine. However, this material has a slower cure rate than the original material. To increase the cure rate, salicylic acid was added as a catalyst. Tests have shown the new material is an acceptable replacement for MDA.

Plastics can be a major proportion of a factory waste stream as a result of manufacturing processes, such as extrusion or injection molding. These wastes result from purging equipment to change plastic type or color, in the case of extrusion, and from mold sprues and runners, and defective parts, in the case of injection molding. (A *sprue* is an extra piece of hardened plastic created during injection molding.) These materials can be granulated and reused. More thermoplastic wastes are being recycled this way within manufacturing plants.

Electroplating, Surface Finishing, and Rinsing

Metal finishing processes are commonly used to inhibit corrosion and provide surfaces suitable for painting. Metal finishing processes also provide functionality, reliability, and long life to electrical components. Unfortunately, many of these processes use hazardous

materials [e.g., hexavalent chromium (Cr^{6+}), cadmium, cyanide, and formaldehyde], or produce hazardous chemical waste, such as volatile organic compounds. One example of an improved electroplating process uses a non-cyanide bath for gold plating. Most of today's gold plating solutions are based on cyanide salts and are considered acutely hazardous. Sandia is evaluating a gold sulfite complex for microelectronic manufacturing applications.³ The gold sulfite is in an alkaline solution with a pH between 8.5 and 11.0. Positive photoresists typically used in commercial microelectronic production facilities are sensitive to alkaline solutions; this sensitivity could present a problem with the new gold bath. We have shown that under controlled electroplating conditions, the standard positive photoresist can be used under normal processing conditions using a photoresist post bake temperature as low as 90° C.

Wet processes such as electroplating and surface finishing involve spraying or immersing parts in aqueous solution. After processing, the parts retain a film of the process solution (dragout) that is removed by a rinsing process. Rinsing processes are critical to produce clean parts but, by their nature, create a waste stream. Indeed, the volume of waste from rinsing is significantly higher than from electroplating. One effective way to handle this type of waste is *recuperative rinsing*. In this process, rinse-water from the first rinse, containing process chemicals, replenishes the process tank, which loses fluid through evaporation. This effectively recycles some or all process chemicals, thereby minimizing waste. AT&T has developed a recuperative rinsing process model that ensures adequate rinsing but minimizes process chemicals and water losses. The recuperative rinsing program analyzes several plating and rinse processes to ensure water conservation and minimal process chemical discharges to waste streams, while not compromising product quality.

Process Monitoring and Control

Process monitoring can automatically obtain and report the information on chemical usage, process quality, and emission levels required by the Environmental

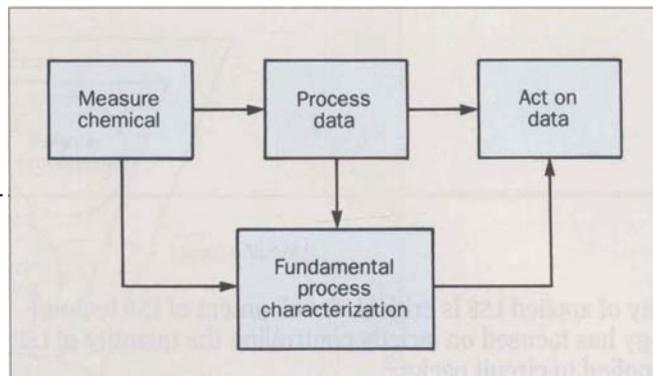


Figure 3. Schematic representation of steps involved in process monitoring and control.

Protection Agency (EPA) and other governmental agencies. Process control can minimize waste, reduce production costs, and improve product quality by detecting and correcting problems early. Figure 3 represents the four steps involved in process monitoring and control. Initially, a chemical sensor or automated analyzer measures the concentration of the chemical (or a physical parameter, such as temperature). Next, the data are analyzed using chemometrics, signal processing techniques or neural networks. (*Chemometrics* are advanced statistical techniques used to process chemical data.) Sandia has pioneered work in this area, especially in applying multivariate calibration methods to quantitative Fourier transform-infrared (FT-IR) analyses.⁴⁻⁶ Neural networks are another approach under study.

After the data have been processed, some action is required. This may simply be an alarm or recording the data for internal use or for reporting to the EPA. A more advanced option is to control the process. This may require regenerating chemicals, changing temperature, pressure, or time. To control a process, one must characterize and model the process, and understand the controlling parameters.

We are developing and applying process monitor and control systems to several manufacturing processes. For example, Sandia is developing an integrated on-line monitoring and control system for electroless copper plating. The electroless copper process is used to plate through-holes in printed circuit board manufacturing. Through-holes provide electrical connections between circuits in separate layers of a laminated multilayer circuit board. The holes are subsequently plated with tin-lead for making solder connections. Typically, electroless copper baths are controlled by monitoring copper, pH,

and formaldehyde; the baths may be replenished manually or automatically. Copper layer thickness is controlled by plating for a specific time. Our monitoring system includes Sandia-developed and commercially available sensors. The Sandia sensors include a fiber optic sensor to measure deposit strain, and a quartz crystal microbalance to measure simultaneously the plating thickness and solution properties. Commercially available probes monitor pH, copper concentration, and temperature.

Sandia has developed FT-IR spectroscopy coupled with chemometrics for process monitoring and control. FT-IR and chemometrics have been used for *in-situ* monitoring of polymer encapsulant mixing. They are also being developed to monitor process chemicals and decomposition products in electroless copper baths.

Design For Environment

To focus on pollution prevention, it is essential to address environmental concerns in the product and process design phase. Decisions made during the design phase have a profound impact on the entire life cycle of the product, from design, through manufacturing, distribution, installation, servicing, and disposal. It has been estimated that from 80 to 90 percent of the total life cycle costs of a product are determined in the design phase.⁷ Integrating the design process with environmental engineering concerns will avoid environmental problems after the design phase. Thus, overall costs associated with process wastes will be reduced.

AT&T has worked to integrate the design process with other functions, using the concept of *DFX*, where *DF* stands for Design For and *X* stands for manufacturability, installability, reliability, safety and other considerations beyond performance and functionality. *DFE* (Design for Environment) will integrate design and environmental engineering to minimize the environmental impact of product manufacture as well as other downstream considerations (see Figure 2).

There are several waste streams associated with a product life cycle, starting with manufacturing, and DFE

approaches to these are being investigated. For example, process design guidelines would help process designers assess the environmental soundness of a new manufacturing process or new equipment. DFE helps process designers to analyze the environmental ramifications of a new process before developing and installing it. By doing a material flow balance or waste audit on a process *before* it is implemented, designers can prevent expensive, intrusive fixes later on.

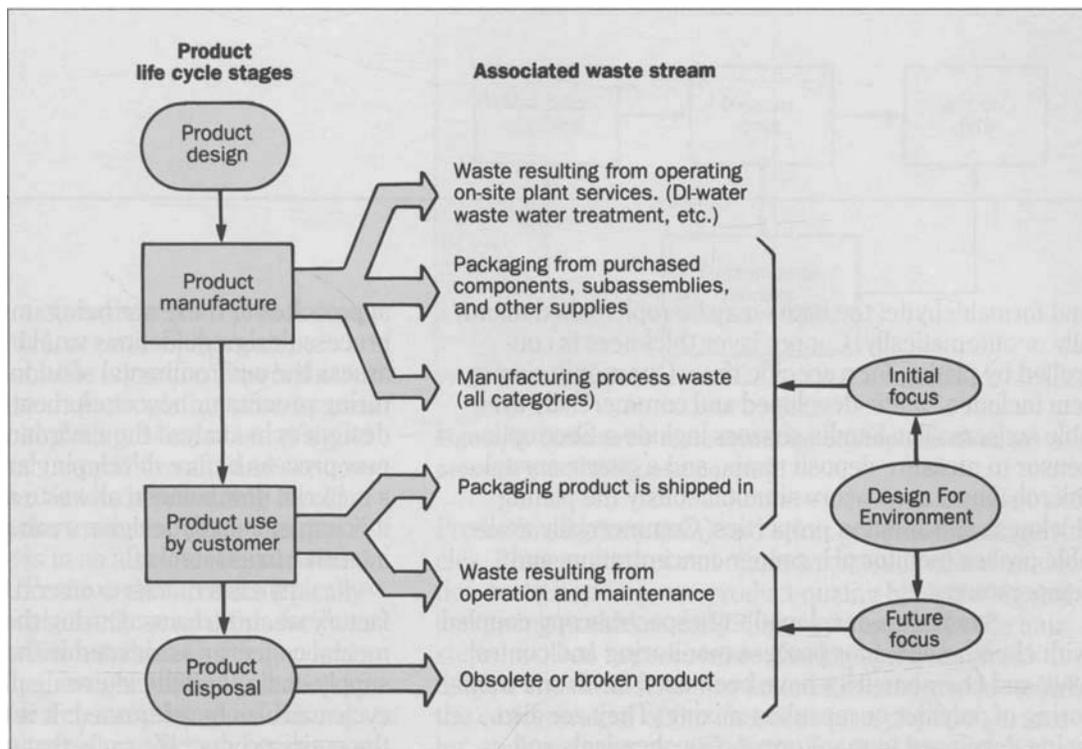
DFE is a means to an end bigger than reducing factory waste streams. During the design stage, environmental concerns associated with the front end (of the supply chain) and the after-sale phase of the product life cycle can also be addressed. It is this idea of influencing the entire product life cycle that makes DFE a potent concept and more than just a waste minimization approach. For example, energy efficiency and final product disposal can be taken into account. *Design for Recyclability* is a concept that illustrates this. A complex product can be designed so it is easy to disassemble into various components and material types for ease of recycling.

DFE is a concept in its infancy that has the potential to significantly impact types and quantities of waste. If done properly, it also has the potential to minimize the environmental impact associated with a product's use and eventual disposal. It is a paradigm shift in managing waste by preventing pollution in the design phase.

Conclusion

Environmentally conscious manufacturing reduces the environmental impact of manufacturing operations. It involves a paradigm shift from end-of-pipe control to meet environmental regulations, to avoiding pollution in the first place (see Figure 4). There are many approaches a company can take, some of which have been summarized here. But the critical point is that ECM is the responsible and economically sound thing to do. It decreases costs and future liability, and often improves the quality of the end-product because of more efficient processes that generate less waste. It is a technology for the 90s.

Figure 4. ECM involves a paradigm shift from the operating practices of the factory of today to the factory of the future where waste minimization is an operating philosophy.



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Biographies (continued)

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