GREEN MANUFACTURING

Mark Atlas and Richard Florida, Carnegie Mellon University

Introduction

There are many ways industrial facilities can implement technologies and workplace practices to improve the environmental outcomes of their production processes (i.e., "green manufacturing") and many motivations for doing so. **Green manufacturing** can lead to lower raw material costs (e.g., recycling wastes, rather than purchasing virgin materials), production efficiency gains (e.g., less energy and water usage), reduced environmental and occupational safety expenses (e.g., smaller regulatory compliance costs and potential liabilities), and improved corporate image (e.g., decreasing perceived environmental impacts on the public) [Porter and van der Linde, 1995].

In general, green manufacturing involves production processes which use inputs with relatively low environmental impacts, which are highly efficient, and which generate little or no waste or pollution. Green manufacturing encompasses **source reduction** (also known as waste or pollution minimization or prevention), **recycling**, and green product design. Source reduction is broadly defined to include any actions reducing the waste initially generated. Recycling includes using or reusing wastes as ingredients in a process or as an effective substitute for a commercial product, or returning the waste to the original process which generated it as a substitute for raw material feedstock. Green product design involves creating products whose design, composition, and usage minimizes their environmental impacts throughout their lifecycle. Because Chapter __ is devoted entirely to green products, it will not be discussed here in detail.

Source reduction and recycling activities already have been widely adopted by industrial facilities. According to 1993 U.S. Environmental Protection Agency Biennial Reporting System data, which cover facilities generating large quantities of hazardous waste, 57% and 43% of these facilities had begun, expanded, or previously implemented source reduction and recycling, respectively. According to a 1995 survey of over 200 U.S. manufacturing companies, 90% of them cited source reduction and 86% cited recycling as main elements in their pollution prevention plans [Florida, 1996].

Organizing for Green Manufacturing

Green manufacturing provides many opportunities for cost reduction, meeting environmental standards, and contributing to an improved corporate image. But finding and exploiting these opportunities frequently involve more than technological problems. The ten most frequently cited waste minimization actions reported by large hazardous waste generators are listed in Table 1.

Table 1. Most Frequently Cited Hazardous Waste Minimization Actions

Percent of All Actions	Waste Minimization Action
8.9%	Improved maintenance schedule, recordkeeping, or procedures
8.0	Other changes in operating practices (not involving changes in equipment)
7.1	Substituted raw materials
6.5	Unspecified source reduction activity
5.1	Stopped combining hazardous and non-hazardous waste
4.8	Modified equipment, layout, or piping
4.6	Other process modifications
4.4	Instituted better controls on operating conditions
4.1	Ensured that materials not in inventory past shelf-life
4.0	Changed to aqueous cleaners

(N = 81,547 waste minimization actions)

Source: Tabulations from 1989, 1991, 1993, and 1995 U.S. Environmental Protection Agency Biennial Reporting System databases.

As the data show, only a small portion of these actions involve new or modified technology. Most involve improving operating practices or controls, or fairly basic ideas -- like waste segregation or raw material changes -- that production workers can suggest and implement. Thus, it is first necessary to organize production operations, management functions, and personnel for green manufacturing to facilitate the identification and development of both technical and common-sense waste minimization ideas [Dillon and Fischer, 1992].

There are several important prerequisites for this process. First, it is critical to have an accounting of inputs, wastes, and their associated costs at each point in the production process. According to 1994 EPA data, 31% of all reported source reduction actions were first identified through pollution prevention opportunity or materials balance audits [EPA, 1996]. The normal financial incentives to reduce costs can be highly efficient within such an accounting system, but the actual efficiency greatly depends on the extent to which true costs are accounted for. The pinpointing of costs, particularly tracking them back to specific production processes, and the projection of future costs are challenging [Florida and Atlas 1997; Todd, 1994]. Second, the facility must know the environmental laws with which it must comply now and in the foreseeable future. This includes environmental permits specifically applicable to it. The facility also must assess the legal implications of possible changes in its operations (e.g., the need for permits if certain changes are made or restrictions on using particular chemicals).

Third, green manufacturing must be a central concern of the facility's top management [Florida and Atlas 1997; Hunt and Auster, 1990]. This is usually helped by outside pressure (from government or environmentalists), or by the convincing demonstration of its benefits (e.g., reduced production costs) [Lawrence and Morell, 1995]. Fourth, it is typically very helpful to involve production workers in green manufacturing [Florida and Atlas 1997; Makower, 1993]. When they are involved in the environmental implications of their activities, they often make substantial contributions, especially improvements in industrial housekeeping, internal recycling, and limited changes in production processes. According to 1994 EPA data, 42% of all reported source reduction activities were first identified through management or employee recommendations [EPA, 1996].

Fifth, green manufacturing will greatly benefit from the easy availability of technical and environmental information about cleaner technology options. Both in-house technical and environmental experts and outside consultants can be useful. It also can be desirable to involve the facility's suppliers and customers in the effort [Georg, Ropke, and Jorgensen, 1992]. Often they can provide solutions not easily perceived by the facility involved in the actual production. Finally, challenging objectives and monitoring of the facility's progress towards achieving them can help in creating effective green manufacturing [Florida and Atlas, 1997]. The targets may be financial (e.g., cost reduction), physical (e.g., input and/or discharge reduction), legal (e.g., lowering emissions to avoid the need for an environmental permit), and personnel (e.g., fewer injuries).

Choosing Green Manufacturing Options

Once the proper organizational approach is established, the first step in choosing options for green manufacturing is making an inventory by production operation of the inputs used (e.g., energy, raw materials, water, etc.) and the wastes generated. These wastes include off-specification products, inputs returned to their suppliers, solid wastes, and other non-product outputs sent to treatment or disposal facilities or discharged into the environment. The second step is selecting the most important non-product outputs or waste streams to focus upon. Their relative importance could depend upon the costs involved, environmental and occupational safety impacts, legal requirements, public pressures, or a combination thereof.

The third step is generating options to reduce these non-product outputs at their origin. These options fall into five general categories: product changes, process changes, input changes, increased internal re-use of wastes, and better housekeeping. The fourth step is to pragmatically evaluate the options for their environmental advantage, technical feasibility, economic sufficiency, and employee acceptability. With respect to economic sufficiency, calculating the pay-back period as discussed in Chapters ___ is usually adequate.

This evaluation usually leads to a number of options, especially in better housekeeping and input changes, which are environmentally advantageous, easy to implement, and financially desirable. Thus, the fifth step is to rapidly implement such options. There typically also are other options which take longer to evaluate, but which usually lead to a substantial number which are worth implementing.

Potential Green Manufacturing Options

As noted earlier, the options for green manufacturing can be divided into five major areas: product changes, production process changes, changes of inputs in the production process, internal re-use of wastes, and better housekeeping. The following discussion focuses on the physical nature of changes which can be implemented (excluding product changes, which are discussed in Chapter __).

Changes in production processes. Many major production process changes fall into the following categories: (1) changing dependence on human intervention, (2) use of a **continuous** instead of a **batch** process, (3) changing the nature of the steps in the production process, (4) eliminating steps in the production process, and (5) changing cleaning processes.

Production dependent on active human intervention has a significant failure rate. This may lead to various problems, ranging from off-specification products to major accidents. A strategy that can reduce the dependence of production processes on active human intervention is having machines take over parts of what humans used to do. Automated process control, robots used for welding purposes, and numerically controlled cutting tools all may reduce wastes.

With respect to using a continuous, rather than batch, process, the former consistently causes less environmental impact than the latter. This is due to the reduction of residuals in the production machinery and thus the reduced need for cleaning, and better opportunities for process control, allowing for improved resource and energy efficiency and decreasing off-specification products. There are, however, opportunities for environmentally improved technology in batch processes. For chemical batch processes, for instance, the main waste prevention methods are (1) eliminate or minimize unwanted byproducts, possibly by changing reactants, processes, or equipment; (2) recycle the solvents used in reactions and extractions; and (3) recycle excess reactants. Furthermore, careful design and well-planned use can also minimize residuals to be cleaned away when batch processes are involved.

Changing the nature of steps in a production process -- whether physical, chemical, or biological -- can considerably affect its environmental impact. Such changes may involve switching from one chemical process to another, or from a chemical to a physical or biological process, or vice versa. In general, using a more selective production route -- such as through inorganic catalysts and enzymes -- will be environmentally beneficial by reducing inputs and their associated wastes. Switching from a chemical to a physical production process also may be beneficial. For example, the banning of chlorofluorocarbons led to other ways of producing flexible polyurethane foams. One resulting process was based on the controlled use of variable pressure, where carbon dioxide and water blow the foam, with the size of the foam cells depending on the pressure applied. An example of an environmentally beneficial change in the physical nature of a process is using electrodynamics in spraying. A major problem of spraying processes is that a significant amount of sprayed material misses its target. In such cases, waste may be greatly reduced by giving the target and the sprayed material opposite electrical charges.

Eliminating steps in the production process may prevent wastes because each step typically creates wastes. For example, facilities have developed processes that eliminated several painting steps. These cut costs and reduce the paint used and thus emissions and waste. In the chemical industry, there is a trend to eliminate neutralization steps which generate waste salts as byproducts. This is mainly achieved by using a more selective type of synthesis.

Cleaning is the source of considerable environmental impacts from production processes. These impacts can partly be reduced by changing inputs in the cleaning process (e.g., using water-based cleaners, rather than solvents). Also, production processes can be changed so that the need for cleaning is reduced or eliminated, such as in the microelectronics industry, where improved production techniques have sharply reduced the need for cleaning with organic solvents. Sometimes, by careful consideration of production sequences, the need for cleaning can be eliminated, such as in textile printing, where good planning of printing sequences may eliminate the need for cleaning away residual pigments. In other processes, reduced cleaning is achieved by minimizing carry-over from one process step to the next. The switch from batch to continuous processes will also usually reduce the need for cleaning.

Changes of inputs in the production process. Changes in inputs is an important tool in green manufacturing. Both major and minor product ingredients and inputs which contribute to production, without being incorporated in the end product, may be worth changing. An example where changing a minor input in production may substantially reduce its environmental impact is the use of paints in the production of cars and airplanes. The introduction of powder-based and high solids paints substantially reduces the emission of volatile organic compounds. Also, substituting water-based for solvent-based coatings may lessen environmental impacts.

Internal re-use. The potential for internal re-use is often substantial, with many possibilities for the re-use of water, energy, and some chemicals and metals. Washing, heating, and cooling in a counter-current process will facilitate the internal re-use of energy and water. Closed-loop process water recycling which replaces single pass systems is usually economically attractive, with both water and chemicals potentially being recycled. In some production processes there may be possibilities for **cascade-type re-use**, in which water used in one process step is used in another process step where quality requirements are less stringent. Similarly, energy may be used in a cascade-type way where waste heat from high temperature processes is used to meet demand for lower temperature heat.

Better housekeeping. Good housekeeping refers to generally simple, routinized, non-resource intensive measures that keep a facility in good working and environmental order. It includes segregating wastes, minimizing chemical and waste inventories, installing overflow alarms and automatic shutoff valves, eliminating leaks and drips and putting collecting devices at places where spills may occur, frequent inspections aimed at identifying environmental concerns and potential malfunctionings of the production process, instituting better controls on operating conditions (flow rate, temperature, pressure, etc.), regular fine-tuning of machinery, and optimizing maintenance schedules. These types of actions often offer relatively quick, easy, and inexpensive ways to reduce chemical and wastes.

Defining Terms

Batch process: A process that is not in continuous or mass production and in which operations are carried out with discrete quantities of material or a limited number of items.

Cascade-type reuse: Input used in one process step is used in another process step where quality requirements are less stringent.

Continuous process: A process that operates on a continuous flow (e.g., materials or time) basis, in contrast to batch, intermittent, or sequential operations.

Green manufacturing: Production processes which use inputs with relatively low environmental impacts, which are highly efficient, and which generate little or no waste or pollution.

Recycling: Using or reusing wastes as ingredients in a process or as an effective substitute for a commercial product, or returning the waste to the original process which generated it as a substitute for raw material feedstock.

Source reduction: Any actions reducing the waste initially generated.

References

Dillon, P. and Fischer, K. 1992. *Environmental Management in Corporations: Methods and Motivations*. Tufts Univ. Press, Medford, MA.

Florida, R. 1996. Lean and Green: The Move to Environmentally Conscious Manufacturing. *Cal. Management Review*. 39: 80-105.

Florida, R. and Atlas, M. 1997. *Report of Field Research on Environmentally-Conscious Manufacturing in the United States*. Carnegie Mellon Univ., Pittsburgh, PA.

Georg, S., Ropke, I., and Jorgensen, U. 1992. Clean Technology -- Innovation and Environmental Regulation. *Environ. Resource Econom.* 2:533-550.

Hunt, C. and Auster, E. 1990. Proactive Environmental Management: Avoiding the Toxic Trap. *Sloan Management Review*. Winter 1990:7-18

Lawrence, A. and Morell D. 1995. Leading-Edge Environmental Management: Motivation, Opportunity, Resources, and Process. In *Research in Corporate Social Performance and Policy, Supplement 1*, ed. J. Post, D. Collins, and M. Starik, p. 99-126. JAI Press Inc., Greenwich, CT.

Makower, J. 1993. *The e Factor: The Bottom-Line Approach to Environmentally Responsible Business*. Times Books, New York, NY.

Porter, M. E. and van der Linde, C. 1995. Green and Competitive: Ending the Stalemate. *Harvard Bus. Rev.* 73:120-134.

Todd, R. 1994. Zero-Loss Environmental Accounting Systems. In *The Greening of Industrial Ecosystems*, ed. B. Allenby and D. Richards, p. 191-200. National Academy Press, Washington, DC.

U.S. Environmental Protection Agency. 1996. *1994 Toxics Release Inventory Public Data Release*. Office of Pollution Prevention and Toxics, Washington, DC.

For Further Information

The Academy of Management has an Organizations and the Natural Environment section for members interested in the organizational management aspects of green manufacturing. For membership forms, contact: The Academy of Management Business Office, Pace University, P.O. Box 3020, Briarcliff Manor, NY 10510-8020. Phone (914) 923-2607. Many of the websites cited below also lead to organizations with particular interests in green manufacturing.

The quarterly *Journal of Industrial Ecology* provides research and case studies concerning green manufacturing. For subscription information, contact: MIT Press Journals, 55 Hayward Street, Cambridge, MA 02142. Phone (617) 253-2889.

There are numerous websites with green manufacturing-related information, including the following: http://es.inel.gov/; http://www.epa.gov/greenlights.html/; http://www.epa.gov/epaoswer/non-hw/reduce/wstewise/index.htm; http://www.turi.org/P2GEMS/; and http://www.hazard.uiuc.edu/wmrc/greatl/clearinghouse.html.