CHAPTER 16

Clean Manufacturing

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1. INTRODUCTION

Clean manufacturing focuses on planning, designing, and producing manufactured products to incur minimal environmental impacts during their lifetimes. Implementation of clean manufacturing includes reliable process control, substitution of hazardous materials with nonhazardous materials, reduction of energy consumption, repair for product life extension, and design for materials recycling. Thus, clean manufacturing may apply to materials and process analyses that reach beyond the manufacturing process to include the environmental impacts of the entire product life. Clean manufacturing requires a broad range of multidisciplinary approaches that include local, regional, national and global policies, engineering and technology advances, economics, and management perspectives.

Industrial engineers study industrial metabolism—that is, the linkages between suppliers, manufacturers, consumers, refurbishers, and recyclers. Environmental engineers, on the other hand, study environmental metabolism—that is, the linkages between entities such as biota, land, freshwater, sea water, and atmosphere (Graedel and Allenby 1995). Clean manufacturing requires the study of the interactions between industrial metabolism and environmental metabolism.

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TABLE 1 Types of Environmental Impacts

General Environmental Impacts	Environmental Hazards
Resource depletion	♦ Materials extraction, use, and disposal ♦ Loss of soil productivity ♦ Landfill exhaustion ♦ Loss of species diversity
Pollutants and wastes	♦ Groundwater quality (biological, metals, and toxic contamination, eutrophication,[a] acid deposition,[a] sedimentation) ♦ Atmospheric quality (stratospheric ozone depletion,[a] global warming,[a] toxic air pollution)
Energy consumption	♦ Energy use that results in resource depletion and/or pollutants

Adapted from Norberg-Bohm et al. 1992.

[a] This term is defined in Section 4.3, Table 6.

2. MOTIVATION

The environmental impacts of manufacturing may include resource depletion, energy consumption, air pollutants, water pollutants, and both hazardous and nonhazardous solid waste. Table 1 shows the hazards associated with general environmental impacts.

2.1. Metrics

The simplest metric for environmental impact with respect to material consumption, pollution, waste generation, or energy consumption is the quantity or inventory for a specified period of time. Microlevel inventory may be measured with respect to a geographical area or industrial facility. Sources for macrolevel inventory data for the United States are summarized in Table 2.

Metrics may also be indexed with respect to a manufacturing output, input, throughput, or batch size, as discussed in Allen and Rosselot (1997). Product-based environmental impact analysis requires activity-based inventory assessment (Stuart et al. 1998). Similar to activity-based costing (see Chapter 89), activity-based environmental inventory assessment recognizes the hierarchy of impacts and assigns them proportionately to an activity such as a product or service.

Due to the complexity of environmental impacts, the Swedish Environmental Institute and Volvo recommend consideration of the following characteristics in their environmental priority strategies (EPS) system: scope, extent of distribution, frequency and intensity, duration or permanence, significance of contribution, and remediability (Horkeby 1997; Ryding et al. 1993). Another complexity to consider is the transfer of impacts along the supply chain because materials extraction, assembly, use, reuse, recycling, and disposal may occur in different locations around the world.

2.2. Legal Requirements

Traditional command-and-control requirements that primarily targeted the manufacturing phase of the product life cycle increased significantly in the past 20 years in the United States. For example, the number of environmental laws passed in the United States increased from 7 between 1895 and 1955 to 40 between 1955 and 1995 (Allenby 1999). Similarly, the number of environmental agreements in the European Union has generally escalated from 1982 to 1995, as described in European Environmental Agency (1997). Many of the regulations in the Asia-Pacific region mirror those in the United States and Europe (Bateman 1999a,b).

TABLE 2 Example of Information Sources for Macrolevel Inventory Data for the United States

Medium	Report	Agency
Material	Toxic Release Inventory (TRI)	U.S. EPA
Pollutant	Aerometric Information Retrieval System (AIRS)	U.S. EPA
Waste	Resource Conservation and Recovery Act Biennial Report System (RCRA BRS)	U.S. EPA
Energy	Manufacturing Energy Consumption Survey	U.S. Department of Energy

Manufacturers must also follow local legislation such as mandates for permits to install or operate processes with regulated effluents. In addition to local and federal mandates where manufacturing and sales take place, manufacturers must also keep abreast of global agreements. For example, the manufacture of chlorofluorocarbon (CFC) solvents, which were used for cleaning electronic assemblies, was banned in 1995 (Andersen 1990). Environmental law is discussed in Chapter 19. Additional legal and service trends are discussed in the next section.

2.3. Responsibility Trends

This section outlines three emerging trends that directly affect the manufacturer's responsibility for environmental impacts: extended product responsibility, extended services, and environmental information reporting. The first trend calls for producers to prevent pollution associated with their products over the products' life cycles. For the second trend, rather than solely selling products, some manufacturers are expanding their business to offer service packages that include the use of their products. In the third trend, the availability and mandatory reporting requirements for environmental information for customers are increasing. These trends are discussed in the next three subsections.

2.3.1. Extended Product Responsibility

There is a trend in Europe and East Asia toward product life cycle responsibility legislation that requires manufacturers to minimize environmental impacts from materials extraction to manufacturing to distribution/packaging to repair to recycling to disposal. Essentially, extended product responsibility shifts the pollution prevention focus from production facilities to the entire product life cycle (Davis et al. 1997). For example, proposed legislation may require that manufacturers not only recycle in-plant wastes but also recycle their discarded products (Denmark Ministry of the Environment 1992; Davis 1997). The evaluation of life cycle stages and impacts are discussed further in Section 4.3.

2.3.2. Manufacturers as Service Providers

In recent years, as manufacturers have assumed the additional role of service provider, responsibility for environmental impact has shifted from the user to the manufacturer. For example, a chemical supplier may be reimbursed per total auto bodies cleaned rather than for the procurement of chemicals for auto body cleaning. Under such an arrangement, there is a financial incentive for the supplier to reduce material consumption (Johnson et al. 1997). In another example, an electronic component manufacturer may use a chemical rental program. The supplier provides chemical management from purchasing and inventory management to waste treatment and disposal (Johnson et al. 1997). Thus, chemical suppliers are gaining a broader responsibility for their products throughout their products' life cycles.

Another important service trend is the replacement of products with services. For example, telecommunications providers offer voice mail rather than selling answering machines. Another example is electronic order processing rather than paper processing. These service trends result in dematerialization, the minimization of materials consumed to accomplish goals (Herman et al. 1989).

2.3.3. Environmental Information Provided by Manufacturers

The third trend is the increasing amount of environmental information that manufacturers communicate to customers. Three general approaches for communicating environmental attributes to corporate procurement and consumers have emerged: eco-labels, self-declaration, and life cycle assessment.

Eco-labels are the simplest format for consumers but the most inflexible format for manufacturers in that they require that 100% of their standard criteria be met. Examples of eco-labels include the Energy Star label in the United States and the Blue Angel in Germany. Because over 20 different eco-labels with different criteria are in use around the world, manufacturers may need to consider multiple eco-label criteria sets (Modl 1995).

Another type of label, self-declaration, allows producers to select methods and metrics. However, comparisons among competing products or services are difficult. Self-declaration is the most flexible form for manufacturers, but its use depends on the manufacturer's environmental reputation among customers. The ECMA, a European industry association that proposes standards for information and communication systems, has proposed product-related environmental attribute standards (Granda et al. 1998).

Full life-cycle assessment, a comprehensive method to analyze the environmental attributes of the entire life cycle of a product, requires environmental engineering expertise. Life cycle assessment is described in Section 4.3.

Consumers may learn about environmental impacts from eco-labels, self-declaration, and life cycle assessment studies. Industrial engineers may learn about clean manufacturing as universities integrate industrial ecology concepts into business and engineering programs (Santi 1997; Stuart 2000). Important clean manufacturing concepts are defined in the next section.

3. HIERARCHY OF IMPORTANT CONCEPTS

To provide a framework for clean manufacturing methods, this section will define important basic concepts. Interestingly, many of the concepts, such as recycling, are defined differently by government, societal, industrial, and academic entities (Allen and Rosselot 1997). Other terms are used interchangeably; for example, *pollution prevention* is often defined as source reduction.

In Table 3, sustainable development and industrial ecology top the hierarchy in clean manufacturing. Industrial ecology is an emerging study that attempts to lessen the environmental impacts of manufacturing activities through planning and design. Industrial ecology is a systems approach to optimizing materials and energy cycles of products and processes (Graedel and Allenby 1995). Methods for clean manufacturing and industrial ecology are described in the next section.

4. METHODS

Traditional methods for clean manufacturing focus on waste or energy audits, which are summarized in Section 4.1. New methods focus on life cycle design, life cycle assessment, production planning models with environmental considerations, and environmental management systems, which are described in Sections 4.2, 4.3, 4.4, and 4.5, respectively.

4.1. Waste/Energy Audits for Waste/Energy Minimization

Waste and energy audits require a detailed inventory analysis of waste generation and energy consumption. The point of origin of each waste and the breakdown of the equipment energy consumption patterns must be determined. Audits are used to identify significant sources of waste and energy costs. Because some environmental impacts are interconnected, both individual source and system impacts must be considered. General guidelines are given for waste audits and energy audits in the next two subsections.

4.1.1. Waste Audits

Waste audits may be performed at the waste, product, or facility level. Waste-level audits simply require that each waste stream and its source be identified. Although this approach is the simplest, it ignores the implications and interactions of the waste stream as a whole. Waste audits performed at the product level are product life cycle inventory assessments, which are discussed in Section 4.3. Facility waste audits are the most common type of audit because most environmental laws require discharge reporting by facility. Estimating plant-wide emissions is discussed in Chapter 19.

Facility waste audits require process flow charts, product material information (commonly from the bill of materials), process material information (such as cutting fluids in a machine shop), and

TABLE 3 Hierarchy of Terms in Clean Manufacturing[a]

Term	Definition
Sustainable development	". . . to meet the needs of the present without compromising the ability of future generations to meet their own needs" (President's Council on Sustainable Development 1996)
Industrial ecology	"the self-conscious organization of production and consumption to reduce adverse environmental impacts of human activity" over time (Socolow 1999)
Product life-cycle assessment	assessment of environmental impacts (materials, energy, and waste) from materials extraction to manufacturing to distribution/packaging to repair to recycling to disposal for a specific product
Pollution prevention[a] or source reduction[a]	product, process, or equipment design that emits fewer pollutants to air, water, and/or land
Waste minimization[a]	in-plant activities to reduce gas, liquid or solid waste
In-process recycling[a]	the nonproduct output is treated and fed back into the process
On-site recycling[a]	waste from a process is converted on-site as a raw material for a different product
Off-site recycling[a]	waste from a process is sent off-site, where it is converted to a raw material for a different product
Waste treatment[a]	waste is treated to lessen its toxicity
Secure disposal[a]	waste is sent to a secure landfill
Direct release[a]	waste is released directly into the environment

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environmental information (solid, liquid, and gaseous wastes). Waste auditing guides are available from state-funded programs (e.g., Pacific Northwest Pollution Prevention Resource Center 1999). Allen and Rosselot suggest that waste audits answer the following series of questions: What waste streams are generated by the facility? in what quantity? at what frequency? by which operations? under what legal restrictions or reporting requirements? by which inputs? at what efficiency? in what mixtures? (Allen and Rosselot 1997)

Waste audits require identification of solid wastes, wastewater, direct and secondary emissions. In the United States, solid wastes may be classified as nonhazardous or hazardous according to the Resource Conservation and Recovery Act (RCRA). In general, wastewater is the most significant component of total waste load Allen and Rosselot (1997). Several methods for estimating the rates of direct (fugitive) and secondary emissions are outlined with references for further information in Allen and Rosselot (1997).

Once companies have identified their major wastes and reduced them, they can turn their focus toward prevention. Pollution-prevention checklists and worksheets are provided in U.S. EPA (1992) and Cattanach et al. (1995). Process- and operations-based strategies for identifying and preventing waste are outlined in (Chadha 1994). Case studies sponsored by the U.S. Department of Energy NICE^3 program detail success stories for cleaner manufacturing or increased energy efficiency for several major industries (see Office of Industrial Technologies, NICE^3, www.oit.doe.gov/nice3/).

4.1.2. Energy Audits

Energy audits may be performed at either the facility or equipment level. Plant-wide energy audits are most common because utility bills summarize energy usage for the facility. Facility energy audits focus on characteristics of use such as occupancy profiles, fuel sources, building size and insulation, window and door alignment, ventilation, lighting, and maintenance programs. (Facility audit forms and checklists are available on the Web from the Washington State University Cooperative Extension Energy Program, www.energy.wsu.edu/ten/energyaudit.htm.) Some industries have developed specialized audit manuals. For example, an energy audit manual for the die-casting industry developed with funds from the state of Illinois and the Department of Energy describes how to assess energy use for an entire die casting facility (Griffith 1997). In addition to industry-specific energy consumption information, the U.S. Department of Energy Industrial Assessment Centers provide eligible small- and medium-sized manufacturers with free energy audits to help them identify opportunities to save energy and reduce waste (Office of Industrial Technologies 1999). Energy management is described in Chapter 58.

At the equipment level, energy usage may be determined through engineering calculations or monitors placed on the equipment in question. Identifying equipment with significant energy consumption may lead to actions such as adding insulation or performing maintenance.

Waste and energy audits are performed to identify existing problems. In the next four subsections, new approaches are presented that focus on prevention through life cycle design, life cycle assessment, production planning models with environmental considerations, and environmental management systems.

4.2. Life-Cycle Design*

The design and implementation of manufacturing activities and products have environmental impacts over time. Thus, industrial ecology requires consideration of the materials and energy consumption as well as effluents from resource extraction, manufacturing, use, repair, recycling, and disposal. Environmental considerations for product design and process design are summarized in the next two subsections.

4.2.1. Product Design

Product design guidelines for clean manufacturing are scattered throughout the industrial, mechanical, environmental, and chemical engineering, industrial design, and industrial ecology literature with labels such as ‘‘life-cycle design,’’ ‘‘design for environment (DFE),’’ ‘‘environmentally conscious design,’’ and ‘‘green design.’’ Traditionally, product design and materials selection criteria included geometric, mechanical, physical, economic, service environment, and manufacturing considerations. Industrial ecology introduces criteria such as reducing toxicity, avoiding resource depletion, increasing recyclability, and improving product upgradeability. The product design criteria in Table 4 are categorized by component and assembly level. As design functions for complex products are increasingly distributed, it is important to recognize product level considerations so that local, component design efforts are not cancelled out. For example, if a simple repair module is inaccessible, the design efforts for easy maintenance will be lost.

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TABLE 4 Product Design Guidelines

	Component-Level Guidelines	Product-Level Guidelines
Process Stage	See Table 5	
Distribution Stage	• Minimize component volume and weight to minimize packaging and energy consumption. • Minimize special storage and transport requirements that lead to extra packaging (e.g., reduce fragility, sharp edges, and unusual shapes). • Design to avoid secondary, tertiary, and additional packaging levels. • Design for bulk packaging.	• Minimize product volume and weight to minimize packaging and energy consumption. • Minimize special storage and transport requirements that lead to extra packaging (e.g., reduce fragility, sharp edges, and unusual shapes). • Design to avoid secondary, tertiary, and additional packaging levels. • Design for bulk packaging.
Use Stage	• Design components with multiple functions. • Consider renewable or rechargeable energy sources. • Minimize energy consumption during start-up, use, and standby modes. • Minimize hazardous material content. • Minimize material content of dwindling world supply or requiring damaging extraction.	• Design product with multiple functions. • Consider renewable or rechargeable energy sources. • Minimize energy consumption during start-up, use, and standby modes. • Minimize use of hazardous joining materials. • Minimize toxicity, quantity, and number of different wastes and emissions.
Refurbishment Repair Upgrade	• Use standard components. • Consider replaceable components. • Use repairable components. • Maximize durability/rigidity. • Consider easily replaceable logos for second market. • Maximize reliability of components.	• Maximize ease of disassembly (access and separation). • Minimize orientation of components. • Design upgradeable modules. • Maximize durability/rigidity. • Consider easily replaceable logos for second market. • Maximize reliability of assembly.
Reclamation/materials recycling	• Maximize use of renewable and/or recyclable materials. • Avoid encapsulates, fillers, paint, sprayed metallic, coatings, labels, or adhesives that reduce recyclability. • Avoid hazardous materials.	• Minimize the number of different materials and different colors; minimize incompatible material combinations. • Use easily identifiable, separable materials; make high-value parts and materials easily accessible with standard tools. • Minimize number of different components and fasteners.

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Because design decisions may result in environmental burden transfers from one stage in the life cycle to another or from one medium to another, it is important to recognize life cycle environmental impacts. Therefore, Table 4 is also categorized by five life-cycle stages: process, distribution, use, refurbishment, and recycling. Note that the process design stage for clean manufacturing is detailed separately in Section 4.2.2 and in Table 5.

One of the emerging themes in Table 4 is dematerialization. Dematerialization focuses on using fewer materials to accomplish a particular task (Herman et al. 1989). For example, consumers may subscribe to periodicals and journals on the Web rather than receive printed paper copies. Clearly, miniaturization, information technology, and the World Wide Web are increasing the potential for

TABLE 5 Process Design and Material Selection Guidelines

- Minimize use of materials with extensive environmental impacts.
- Minimize toxic emissions.
- Minimize material and water consumption.
- Minimize energy consumption.
- Consider materials that allow in-process, on-site, and off-site recycling.
- Perform preventive maintenance to reduce environmental impacts over time.
- Minimize secondary processes such as coatings.
- Eliminate redundant processes.
- Minimize cleaning process requirements.
- Capture wastes for recycling, treatment, or proper disposal.

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dematerialization. Evaluating the criteria in Table 4 to avoid resource depletion or to use renewable materials requires assumptions to be made regarding the uncertainties in technological improvement, material substitutability, and rates of extraction and recycling (Keoleian et al. 1997).

The design criterion to increase product life reduces the number of products discarded over time. In the mid-1970s, DEC VT100 terminals could be disassembled quickly without tools to access the processor for maintenance and upgrades (Sze 2000). In 1999, the Macintosh G4 was introduced with a latch on the side cover that provides quick access to upgrade memory and other accessories (Apple 1999). Product life extension is especially important for products with short lives and toxic materials. For example, battery manufacturers extended the life of nickel–cadmium batteries (Davis et al. 1997). An example of product toxicity reduction was the change in material composition of batteries to reduce mercury content while maintaining performance (Tillman 1991). In another example, popular athletic shoes for children were redesigned to eliminate mercury switches when the shoes were banned from landfills (*Consumer Reports* 1994). The criteria related to recyclability may apply to product material content as well as the processing materials described in the next section.

4.2.2. *Process Design*

The criteria for process design for clean manufacturing focus on minimizing pollution, energy consumption, water consumption, secondary processes, or redundant processes. Table 5 provides a summary of suggested guidelines for materials selection and process design.

Careful process design can reduce environmental impacts and processing costs. For example, many companies eliminated the cleaning step for printed circuit card assembly by changing to low-solids flux and controlled atmospheres. These companies eliminated the labor, equipment, materials, and waste costs as well as the processing time associated with the cleaning step (Gutierrez and Tulkoff 1994; Cala et al. 1996; Linton 1995). Another example of reducing processing material consumption is recycling coolants used in machine shops. Recycling coolant reduces coolant consumption as well as eliminates abrasive metal particles that can shorten tool life or scar product surfaces (Waurzyniak 1999).

4.3. Product Life-Cycle Assessment*

Life-cycle assessment (LCA) is a three-step design evaluation methodology composed of inventory profile, environmental impact assessment, and improvement analysis (Keoleian and Menerey 1994). The purpose of the inventory step is to examine the resources consumed and wastes generated at all stages of the product life cycle, including raw materials acquisition, manufacturing, distribution, use, repair, reclamation, and waste disposal.

Materials and energy balance equations are often used to quantify the inputs and outputs at each stage in the product life cycle. Vigon et al. (1993) defines multiple categories of data for inventory analysis, including individual process, facility-specific, industry-average, and generic data. The most desirable form of data is the first data category, data collected from the process used for a specific product. However, this data category may require extensive personnel, expertise, time, and costs.

A three-step methodology for activity-based environmental inventory allocation is useful in calculating data for the first step of life cycle assessment. First, the process flow and system boundary

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are determined. Then the activity levels and the activity percentages of the inputs and outputs are identified. Finally, the activity percentages are used to determine the actual quantities of the inputs and outputs and assign them to the product and process design combination responsible for their generation. A detailed example of this method is given in Stuart et al. (1998). As industrial engineers assist companies in calculating the allocation of their wastes to the product responsible, they can help managers make more informed decisions about product and process design costs and environmental impacts.

Industry-average and generic data must be used with caution because processes may be run with different energy requirements and efficiencies or may exhibit nonlinear behavior (Barnthouse et al. 1998; Field and Ehrenfeld 1999). For example, different regions have different fuel-producing industries and efficiencies that will have a significant effect on the LCA if energy consumption is one of the largest impacts (Boustead 1995).

Once the inputs and outputs are determined, the second and third steps of LCA, impact analysis and improvement analysis, can be pursued (Fava et al. 1991). For impact analysis, the analyst links the inventory of a substance released to an environmental load factor such as acid deposition, which is defined in Table 6 (Potting et al. 1998). Environmental load factors are a function of characteristics such as location, medium, time, rate of release, route of exposure, natural environmental process mechanisms, persistence, mobility, accumulation, toxicity, and threshold of effect. Owens argues that because inventory factors do not have the spatial, temporal, or threshold characteristics that are inherent to the environmental load, other risk-assessment tools should be used to evaluate a local process (Owens 1997).

LCA software tools and matrices may be used to estimate environmental load factors for impact analysis (Graedel 1998; Graedel et al. 1995). Alting and Legarth (1995) review 18 LCA tools for database availability, impact assessment methodology, and complex product capability.

The results of life-cycle impact assessment (LCIA) provide relative indicators of environmental impact. Eight categories for LCIA are defined in Table 6. Details regarding how to use life cycle impact assessment categories are provided in Barnthouse et al. (1998) and Graedel and Allenby (1995).

Life cycle assessment is a comprehensive, quantitative approach to evaluate a single product. "An extensive survey of the use of mathematical programming to address environmental impacts for air, water, and land is given in [Greenberg (1995)]. A review of applied operations research

TABLE 6 Environmental Categories for Life-Cycle Impact Assessment

Environmental Category	Description
Greenhouse effect Global warming	Lower atmospheric warming from trapped solar radiation due to an abundance of CO_2, CH_4 (methane), N_2O, H_2O, $CFCl_3$, CF_2Cl_2, and O_3 (ozone) (Graedel and Crutzen 1990)
Ozone depletion	Losses in stratospheric ozone due to $CFCl_3$ and CF_2Cl_2 (Graedel and Crutzen 1990)
Photochemical smog	Reactions in the lower troposphere caused by emissions such as NO_x gases and hydrocarbons from automotive exhaust (Theodore and Theodore 1996)
Consumption of abiotic resources	Consumption of nonliving (nonrenewable) substances
Acid deposition	Acidic precipitation that deposits HNO_3 and H_2SO_4 into soil, water, and vegetation (Graedel and Crutzen 1990)
Eutrophication	Large deposits of phosphorous and nitrogen to a body of water that leads to excessive aquatic plant growth, which reduces the water's oxygen levels and capacity to support life (Theodore and Theodore 1996; Riviere 1990)
Ecotoxity	Substances that degrade the ecosystem either directly (acute) or over time (chronic) (Barnthouse et al. 1998; Graedel and Allenby 1995)
Habitat loss	Encroachment by humans into biologically diverse areas, resulting in the displacement and extinction of wildlife
Biodiversity	Living species that constitute the complex food web (Graedel and Allenby 1995)

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papers on supply chain analysis and policy analysis with respect to environmental management is in [Bloemhof-Ruwaard et al. (1995)]" (Stuart et al. 1999). Models for production planning with environmental considerations are summarized in the next section.

4.4. Production Planning with Environmental Considerations

"Introduction of product designs and process innovation requires a company to evaluate complex cost and environmental tradeoffs. In the past, these have not included environmental costs" (Stuart et al. 1999). In this section, production planning models are described for the entire product life cycle as well as for different stages of the product life cycle.

4.4.1. Models for Production Planning over the Product Life Cycle

Stuart et al. (1999) developed the first mixed integer linear programming model "to select product and process alternatives while considering tradeoffs of yield, reliability, and business-focused environmental impacts. Explicit constraints for environmental impacts such as material consumption, energy consumption, and process waste generation are modeled for specified assembly and disassembly periods. The constraint sets demonstrate a new way to define the relationship between assembly activities and disassembly configurations through take-back rates. Use of the model as an industry decision tool is demonstrated with an electronics assembly case study in Stuart et al. (1997). Manufacturers may run "what if" scenarios for proposed legislation to test the effects on design selection and the bottom line cost impacts." The effects over time of pollution prevention or product life extension are analyzed from a manufacturer's and potentially lessor's perspective. Several new models explore the relationship between product and component reuse and new procurement. These models include deterministic approaches using mixed integer linear programming (Eskigun and Uzsoy 1998) and stochastic approaches using queueing theory (Heyman 1977) and periodic review inventory models (Inderfurth 1997; van der Laan and Salomon 1997). Location of remanufacturing facilities are analyzed in Jayaraman (1996); Bloemhof-Ruwaard et al. (1994, 1996); Fleischmann et al. (1997). Scheduling policies for remanufacturing are presented in Guide et al. (1997).

4.4.2. Production Planning Models for the Manufacturing and Assembly Stage

Early models focused on reducing the environmental impacts concurrent with process planning for continuous processes in the petroleum and steel industries (Russell 1973; Russell and Vaughan 1974). Recently, models with environmental considerations focus on process planning for discrete product manufacturing (Bennett and Yano 1996, 1998; Sheng and Worhach 1998).

4.4.3. Disassembly Planning Models

Based on graph theory, Meacham et al. (1999) present a fast algorithm, MAXREV, to determine the degree of disassembly for a single product. They are the first to model selection of disassembly strategies for multiple products subject to shared resource constraints. They use their MAXREV algorithm to generate maximum revenue disassembly configurations for their column generation procedure for multiple products. Other disassembly models based on graph theory approaches focus on determining economic manual disassembly sequences for a single product (Ron and Penev 1995; Penev and Ron 1996; Zhang and Kuo 1996; Johnson and Wang 1995; Lambert 1997). A process planning approach to minimize worker exposure hazards during disassembly is given in Turnquist et al. (1996). Disassembly may be economically advantageous for module and component reuse. However, for material recovery, escalating labor costs favor bulk recycling.

4.4.4. Production Planning Models for Bulk Recycling

Production planning for bulk recycling is in the early stages of development. Models include a macro-level transportation model for paper recycling (Glassey and Gupta 1974; Chvatal 1980) and a goal-programming model for recycling a single product (Hoshino et al. 1995). Sodhi and Knight (1998) develop a dynamic programming model for float–sink operations to separate materials by density. Spengler et al. (1997) present a mixed integer linear programming model to determine the manual disassembly level and recycling quantity. Stuart and Lu (2000) develop a multicommodity flow model to select the output purity by evaluating various processing and reprocessing options for bulk recycling of end-of-life products. Isaacs and Gupta (1998) use goal programming to maximize disassembler and shredder profits subject to inventory balance constraints for the automobile recycling problem. Krikke et al. (1998) propose dynamic programming for disassembly planning and an algorithm to maximize revenue from material recycling. Realff et al. (1999) use mixed integer linear programming to select sites and determine the amount of postconsumer material collected, processed, stored, shipped, and sold at various sites.

4.5. Environmental Management Systems

An environmental management system (EMS) is a management structure that addresses the long-term environmental impact of a company's products, services, and processes. An EMS framework should include the following four characteristics:

1. Environmental information collection and storage system
2. Management and employee commitment to environmental performance
3. Accounting and decision processes that recognize environmental costs and impacts
4. Commitment to continuous improvement of environmental performance

Federal U.S. EMS guidelines and information are documented in (Department of Energy 1998). International standards for EMS will be discussed in Section 4.5.3. Environmental management systems (EMS) include environmental policies, goals, and standards, which are discussed in the next three subsections.

4.5.1. Corporate Environmental Policies

Corporate environmental policies require the commitment and resources of senior management. These policies often focus on actions that can prevent, eliminate, reduce, reuse, and recycle, respectively. These policies should be incorporated into all employees' practices and performance evaluations. Communication of environmental policies and information is integral to the success of the policies. Setting viable goals from corporate environmental policies is the subject of the next section.

4.5.2. Environmental Goals and Metrics

Traditional environmental metrics often focus on compliance with legislation. Goals may concentrate on state-dependent benchmark metrics such as reducing emissions, reducing the volume or mass of solid waste, or reducing gallons of waste water to a specified level. On the other hand, goals may focus on non-state-dependent improvement metrics such as reducing the percentage of environmental treatment and disposal costs. It is also important to distinguish between local and aggregate data when developing goals.

Metrics may focus on local product or process goals or system-wide facility or company goals. An example of a local goal might be to lengthen tool life and reduce cutting fluid waste disposal costs. Sometimes local goals may translate to system goals. One machinist's use of a new oil-free, protein-based cutting fluid that eliminates misting and dermatitis problems but provides the necessary lubricity and cooling may be a candidate for a system-wide process and procurement change (Koelsch 1997). With local goals, it is important to investigate their potential positive and negative impacts if implemented throughout the system. An example of a system-wide goal might be to reduce the percentage of polymer sprues and runners discarded at a particular facility by implementing regrinding and remolding or redesigning the mold. For system goals, it is important to identify the most significant contributors through Pareto analysis and target them for improvement.

4.5.3. ISO 14000 Series Standards

ISO 14001, "an international standard describing the basic elements of an environmental management system, calls for identification of the environmental aspects and impacts of a company's products, processes, and services [Block 1997]. Industrial engineers may develop the information systems to quantify environmental aspects such as input materials, discharges, and energy consumption [Alexander 1996]" (Stuart et al. 1998).

5. CONCLUDING REMARKS

Clean manufacturing is an important concept to integrate into industrial engineering methodologies. Traditional waste and energy audits help companies identify cost and environmental savings opportunities. New concepts such as life cycle design, product life cycle assessment, production planning with environmental considerations, and environmental management systems help companies to prevent costly negative environmental impacts. In summary, clean manufacturing provides opportunities for increased efficiencies and cost effectiveness as well as movement towards sustainability.

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