Technovation, 15(2) (1995) 79–97

Manufacturing strategy and environmental consciousness

Joseph Sarkis
Department of Information Systems and Management Sciences, University of Texas at Arlington, Arlington, TX 76019, USA

Abstract

Ecological and environmental issues are playing a larger role in corporate and manufacturing strategies. Global and domestic environmental regulations and laws are forcing many organizations to consider environmental impacts of all functions and business processes and products. In this paper the environmental consciousness issues pertaining to manufacturing and operations management are presented. A general strategic framework on how to manage environmentally conscious programs and projects in a manufacturing enterprise is also developed and discussed. A number of research initiatives that need to be pursued are identified. The pursuit of these research initiatives will alleviate many of the barriers to adoption of environmentally conscious manufacturing strategies.

1. Introduction

The need for environmentally benign manufacturing technology and processes will be a prerequisite for manufacturing enterprises competing in most global markets. The need to incorporate environmental factors and parameters into corporate strategies and policies will be required for enterprises to be competitive or to maintain a competitive edge. This is evidenced by a survey of 41 Fortune 200 non-service firms that shows that environmental management is becoming central to corporate strategy and is being managed as an arena of competition rather than as a compliance-driven function [1]. It has also been found that in a recent survey of CEOs, 90% agreed that the environmental challenge was sure to be one of the central issues of the next century [2]. However, many firms have not embraced environmentally friendly practices. A survey conducted by the National Association of Environmental Managers showed that companies employing an environmental manager consider the responsibility to be mainly one of compliance. Almost none thought in terms of improvement in design or process. Over the past couple of decades there have been a number of manufacturing and organizationally oriented process strategies and technologies that have been gaining attention among organizations in order to improve the competitive stances of these enterprises. These technologies and strategies have been shown to impact the profitability, flexibility, quality, and productivity of the enterprises. Additionally, it can be shown, through an appropriate strategic framework, that these strategic choices will have significant impact on environmental and ecological factors.

In order to aid manufacturing and operations

 0166-4972/95/US$07.00

managers and researchers, we identify various issues, methods and tools that will help them to understand and link manufacturing strategies and technology with environmental and ecological concerns. In this paper we have also identified and reviewed a comprehensive set of literature and previous work that has been carried out relative to environmentally conscious manufacturing (ECM) practices in both the global and domestic environments. We provide various tools and possible research agendas that need to be pursued by both academia and industry. To help in the execution of these strategic programs, a general management framework is also presented.

2. Manufacturing strategy and strategy development background

Manufacturing strategy provides a vision for the manufacturing organization based on the business strategic plan. It consists of objectives, strategies, and programs which help the business gain, or maintain, a competitive advantage [3]. The role of manufacturing strategy in manufacturing enterprises has become more visible in recent years. Initially, it was viewed as an operational consideration and planning was short-term and very focused within the manufacturing function. Skinner [4] was one of the earliest proponents of corporations developing and integrating manufacturing strategy into the overall business strategy. The common dimensions within manufacturing strategy, as presented in the literature, include product-, process-, and technological-related strategies [5, 6]. Each of these dimensions are also linked closely to various environmental issues facing manufacturing enterprises. Our discussion of various ECM issues will outline the ECM strategy relationships with these general manufacturing strategy dimensions.

ECM involves the planning, development and implementation of manufacturing processes and technology that minimize or eliminate hazardous waste, reduce scrap, are operationally safer, and can design products that are recyclable, or can be remanufactured or reused [7]. Expected benefits of ECM include safer and cleaner facilities, reduced future costs for disposal and worker protection, reduced environmental and health risks, and improved product quality at lower cost and higher productivity. To begin integrating ECM into the corporate strategy, some background in corporate strategy development is presented.

The standard approach to the development of a corporate strategy and the role it plays in a corporation, as defined by Porter [8], is first to determine a mission for the organization. The mission then drives objective formation, which gets interpreted into strategy policies for the overall organization. This is defined as the mission, objectives, strategy, and policy (MOSP) setting process. The drive for the MOSP process is consideration of the external competitive environment of the organization. This is accomplished by focusing on competitors' strengths and weaknesses, and from these, determining the firm's opportunities and threats (SWOT). To help in carrying out a SWOT–MOSP environmental strategy development process, a general open systems model, to carry out the linkage of external and internal interactions for the planning and control of corporate environmental strategy, has been developed by Klassen [9]. This approach provides insight into the characteristics of the internal and external processes that interact to form the strategies for an organization. Interacting with the manufacturing strategy are other functional strategies, which are also constrained by the overall business strategic plan.

These functional strategies (manufacturing, marketing, etc.) must clearly fit within, and not conflict with, the overall business strategies. Thus, it is imperative that a corporate strategy must include as one of its dimensions environmental consciousness from all functions within the organization, not just manufacturing. Each of these functional areas will also have a profound impact on the development and implementation of a manufacturing strategy. Evidence of the importance of explicitly and proactively including and addressing environmental issues in corporate strategy is provided by the external pressures from various sources. From the marketing and finance focus of the corporate strategy, these external pressures have been defined as 'green consumerism'. Some of the key players and drivers of green consumerism include: (1) environmental groups, (2) 'green' voters, (3) the business-to-business sector, (4) retailers, (5) employees, and (6) shareholders [10]. There are a number of general environmentally based business strategies that a manufacturing enterprise would want to pursue, a partial listing of which is as follows [10, 11]:

- reduce consumer skepticism by forming alliances with environmental groups, regulators, retailers, and academia;
- practice pollution prevention at the source;
- stay ahead of current, and anticipate future, environmental standards;
- avoid doing business with suppliers that take ecological shortcuts;
- make every individual in the organization assume responsibility for environmental protection;
- take preventive and corrective environmental action;
- measure for environmental impact;
- promote self-organizing systems by empowering people to act to prevent pollution.

These strategies must filter down to the various functional objectives which will drive the functional strategies. A detailed outline of the functional strategies and their interfaces among each other as well as the linkages with the corporate policies and strategies is well established in the literature [12–18].

Many of the major external issues and pressures that will drive the corporate and functional strategies are from governmental and regulatory sources.

2.1 Global ECM strategies

Clearly, one of the more important external competitive environmental factors that will influence the development of corporate strategies are the efforts by other corporations and enterprises, especially international competitors. The environmental issues and factors that various global manufacturers are researching and developing will be a major incentive for the development of US domestic corporate strategy. Table 1 summarizes a number of industrial efforts that are on-going in Japan in various industries. Many of these programs are joint efforts among groups of industrial members and the Japanese government. Table 1 also shows the pervasiveness of environmental research programs among a variety of industries, not just manufacturing-related ones. Included among these examples are strategies that focus on product-related initiatives (batteries, automobiles), process-related initiatives (sortation and transportation systems, redesign of plants) and technology-related initiatives (Ecofactory, fuel cell technology).

The Japanese government is also financing a major effort through the Ministry of International Trade and Industry (MITI) in a program called Ecofactory. The ecofactory concept ". . . aims to establish next-generation mechanical engineering contributing to the resolution of global environmental disruption problems without impairing the manufacturing economy or activities for technological progress" [19].

The major driving force for the development of ECM practices and technology for the Japanese is not only for competitive advantage, but also because of environmental necessity. This necessity is primarily due to Japan's limited geographical area and natural resources. Ecofactory's initiatives focus primarily on various manufacturing technology strategies. The major emphasis for manufacturing technology is on production systems, restoration systems, and control and assessment technology. Various technologies within each of these groupings are shown in Fig. 1. These technology-oriented strategies are currently driving some of the domestic corporate ECM research and development.

European ECM initiatives have also been getting considerable attention. The European programs focus heavily on recycling, and implementing recyclable and environmentally conscious features

TABLE 1 Japanese industry environmental strategies (adapted from refs. [67, 68])

Industry/Company	Strategy
Automobile industry	Redesigned cars to increase fuel efficiency and reduce the emission of carbon dioxide. Included the use of lighter body materials, lean-burn engines and improved catalytic converters. Introduction of electric cars with capabilities of 109 mph and 340 mile range on a single battery charge
Construction industry	Developed integrated systems to sort and transport waste within office buildings and complexes
Ebara Corp.	Introduction of powerful low-emission industrial waste incinerators
Electric power industry	Engaged in research to convert sulfur and nitrogen oxides into ammonium sulfate and ammonium nitrate for use in fertilizer. Leaders in fuel cell technology and solar batteries. Results in lessening of greenhouse gas emissions
Fuji Electric Company	Leader in fuel cell technology. Results in lessening of greenhouse gas emissions
Ishikawajima–Harima Heavy Industries	Introduction of nitrogen oxides removal technology for industry and power plants
Matsushita Battery Industrial Corp.	Introduction of first mercury-free alkaline batteries
Ministry of International Trade and Industry	Project on the use of biotech to make hydrogen Supporting the development of the Ecofactory concept
Mitsubishi Heavy Industries	Teamed to develop chemical catalysts to remove nitrogen oxides from coal-fired power plants
Nippon Steel Corp.	Conversion of steel ash to zeolite, a mineral used in water treatment
Steel industry	Responsible for 25% of the carbon dioxide emission and 35% of industrial waste in Japan. Energy consumption slashed by 20% since the mid-1970s. Seeking to further reduce energy use by 10%. Plants designed to recycle more heat and waste

in products and processes. These efforts include research and development in ECM alternatives in recycling, design for disassembly, infrastructure, and standards. One large consortium of European countries and industry, called EUREKA [20], has over 117 environmental projects underway. Twenty-two percent of a $1.2 billion budget is allocated to these projects. There are also a number of individual countries that have focused their efforts on R&D programs: Germany is budgeting $470 million to focus on environmental technologies; The Netherlands has subsidized industry with $90 million to support the development of clean technology such as integrated recycling and associated processes; the United Kingdom has focused research efforts to address the possibility of European Community mandatory 'take-back' legislation for various electronic and automotive products [21]. Take-back is currently being practised by the German government, where the automotive industry has been required to retrieve its vehicles for environmentally sound disassembly and disposal [22, 23]. The take-back policy is also being considered by other countries and for other products.

European industry has also established a group to oversee the propagation of life-cycle assessment techniques. This group is conducting a feasibility study on the creation of a database of life-cycle inventories for commodities such as basic chemical feedstocks, electricity, packaging, water and services [24]. This shows the importance of and need for integration of information technologies and systems on a large scale. Later, we go into more detail about the fundamental elements and issues facing life-cycle assessment.

Additional international practices which are influencing various corporate functional strategies include recognition of and compliance with environmentally conscious practices through 'eco-labels'. These labels include Germany's Blue Angel, Canada's Environmental Choice, Japan's Ecomark and Norway's Nordic Environmental Label, among others (see [25]). These labeling systems are controlled by consumer/environmental groups and/or government agencies. No general

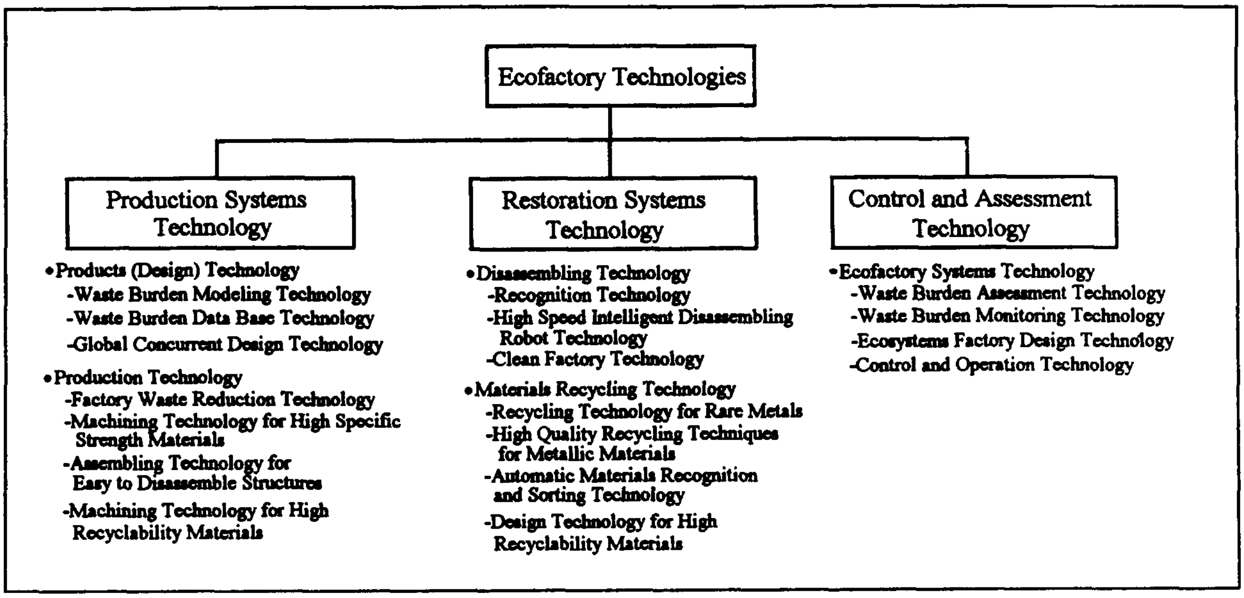

Fig. 1. Ecofactory technology strategies

comparable eco-labels currently exist in the US, except for the standard recyclability type symbols that appear on products. It is likely that a private organization or marketers may initially oversee eco-labeling in the US [26]. This type of labeling may result in a set of standards, similar to ISO 9000 quality standards, that directly identify environmentally conscious organizations and products and have implications for future domestic business practices, as well as domestic corporations seeking to do business in these international marketplaces. One such set of standards already exists in Britain under British Standard 7750 (from which the same family of standards, the ISO 9000 standards, evolved) which has specifications for Environmental Management Systems [27].

In summary, a number of European, Japanese and other global efforts for ECM have been driven by government regulations, with collaborative efforts by government and industry. Compliance and cooperation go hand in hand in these marketplaces, and are having a profound impact on US ECM practices.

2.2 Domestic ECM initiatives

Similar to global ECM initiatives, strong external forces for domestic corporate initiatives are governmental and regulatory environmental legislation. The amount of environmentally related legislation in the past three decades has increased five-fold, from nine major acts and laws to over 45 [28]. It is expected that this pattern will continue to rise at the same rate.

Domestic environmental and governmental agencies, in a similar manner to international practices, have evolved from one of oversight, through regulatory and punitive approaches, to promotion of cooperative and preventive practices. A number of government support programs seeking to educate domestic manufacturers and aid various research efforts are currently underway. The major driving force of many of these programs is the US Environment Protection Agency (EPA), which has supported programs that focus more on pollution prevention and waste assessment approaches primarily through its risk reduction engineering laboratory (for example, see [29]), rather than just punitive and oversight programs (such as 'superfund' activities). The EPA's pollution prevention research branch has programs focusing on clean products, processes research, technology transfer, recycling, and socioeconomic issues [30]. Other governmental agencies such as the Departments of Energy, Commerce and Defense have research and development programs that have focused on environmentally friendly technology, processes and product development.

Industry groups have also joined together cooperatively to research and develop various 'clean' and environmentally conscious technology. A major consortium of over 200 companies that is looking into these issues is the National Center for Manufacturing Sciences [31], which has a strategic interest group focusing primarily on ECM technology and tools. Some of the major projects include (1) material compatibility in electronic components, (2) organic contaminant specification in electronics, (3) solventless cleaning of electronic components, (4) alternatives for fatigue propagation in metal parts, (5) tools for disassembly planning, (6) assessment of alternative solvents and (7) reduction of lead use in manufacturing. Industry-specific professional and consortia groups have also looked at ECM practices in their industries. Examples of this are the efforts by the domestic electronics industries to research the issues for life-cycle assessments of computer and electronics products [20]. The appliance industry has looked into various aspects of design for disassembly (disassembly concepts are discussed below). There has been a call by the appliance industry to utilize the same principles as the European automobile manufacturers in carrying out life-cycle assessments of appliances [32, 33].

Major ECM strategy initiatives have been carried out by individual organizations. For example, General Electrics Plastics has taken what it has learned from using disassembly and recyclability concepts that were used to design BMW automobiles and applied them to home appliances. Dupont, Grumman, Hewlett Packard, IBM, Kimberly Clark, 3M, Xerox, and a number of other companies have had various projects that have looked into the various ECM elements that we will be describing in the next few sections.

3. Components and tools of ECM

In this section we will discuss and review some of the various components of the ECM environment, including strategies and their current and emerging research issues. The major topical areas will be the life-cycle assessment, remanufacturing, recycling/reuse and reduction strategies. A multi-dimensional relationship exists among these categories, which will be summarized in Table 2. We will use the product development life cycle and life-cycle assessment as the guiding framework for presentation of the various elements of these ECM strategies.

3.1 Product development life cycle and life-cycle assessment

One of the most effective approaches to view the results of corporate manufacturing initiatives is through product development life-cycle (PDLC) assessments. This process involves viewing the product from 'cradle-to-grave' (or if it were to include the various strategies, 'cradle-to-cradle'). The PDLC approach is useful in examining the environmental impacts, seen and unforeseen, of a product. The ability to view the environmental impacts will require viewing the PDLC as part of an integrated set of business processes. This can be achieved by having a functional representation of the business processes within an organization, or a set of enterprise models. An enterprise model made up of a set of integrated activities allows for analysis based on cost and business process activities, as well as the relationship to any waste streams generated by these activities.

Traditional applications of life-cycle assessment approaches have focused on the product's manufacturing life-cycle and the selection of alternative product characteristics, especially types of materials to be used in the manufacturing of a product. This approach can be broadened to include analysis of alternative processes and technology that can be used to produce the same product. The life-cycle of a product can be viewed in the flow chart shown in Fig. 2. In Fig. 2, we identify three primary phases of the life-cycle from an operations perspective, procurement, production and distribution. This model provides an elementary look at a product's life-cycle; another model that is often used for life-cycle analysis is Porter's value chain [8]. Within the chain described in the figure, we see that reduction of waste generated by any of these activities is a major goal for ECM strategies. Any waste that cannot be eliminated has the opportunity to be recycled, reused, remanufactured or disposed of. The general goal is to keep all materials within the life-cycle, and thus minimize any flow into the external environment. In this case the only strategy that conflicts with this goal and should be eliminated or minimized is that of disposal. Even in the 'after-market', the product and materials can follow the same ECM strategies to integrate the product back into the life-cycle. The feedback arrows show the general paths that products and material will follow when one of these strategies is used. As an example, if a product is recycled it will most likely enter the life-cycle chain in the procurement stage, where it may be utilized with raw material to produce the virgin material after some initial processing. The other strategies also follow these general paths, but may differ slightly depending on the manufacturing environment, industry and product type. The characteristics of each of these strategies are described in more detail in the following sections.

The basic argument for life-cycle assessment methodologies from a manufacturing point of view has been succinctly stated by Frosch and Gallopoulos [34]:

> *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. An example of some of the subtleties involved is a car that is made lighter for improved energy use, but the material that has made the automobile lighter is more expensive to recycle than the older material.*

'Standardized' life-cycle assessments for products and materials are now being completed by industries as well as individual enterprises. In the future, life-cycle assessments are expected to play a large role in shaping public policy, and may become even

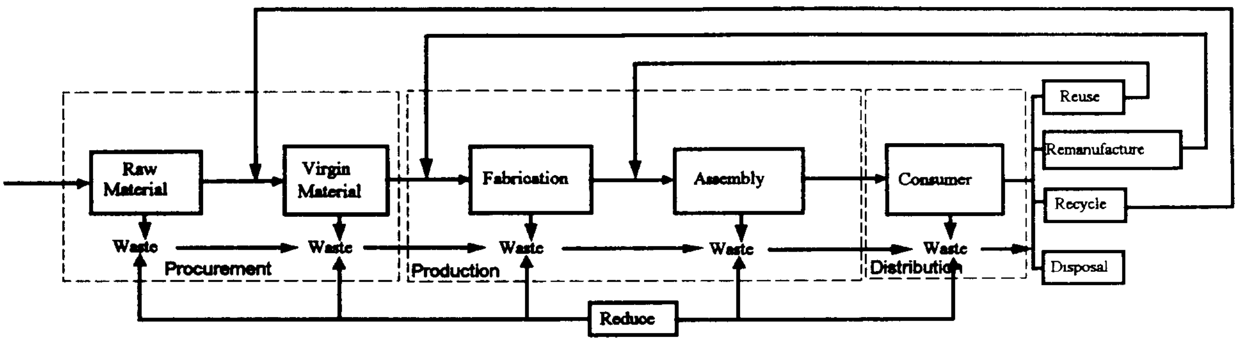

Fig. 2. Operational stages of a life-cycle assessment

more important in corporate strategy development [24]. This is already seen in the various joint initiatives that are occurring in various international marketplaces, as described earlier.

Life-cycle assessment methodologies and tools have to consider both the flow of materials and their linkages and relationships among the activities and processes concerned. Use of enterprise or systems modeling tools will be necessary in order to provide a more accurate and complete picture of the interrelated activities. Systems modeling techniques that have proved helpful in enterprise modeling are the Integrated Computer Aided Manufacturing Definition (IDEF) modeling techniques that were developed by the Air Force's ICAM project in the late 1970s and early 1980s. The functional modeling approach of IDEF is defined as IDEF0. The product development life-cycle (PDLC) shown in Fig. 3 represents a concurrent engineering (or Design for 'X') approach where the product is designed for a number of future life-cycle occurrences such as manufacture, maintenance, recycling, disposal and the environment. Concurrent engineering is a systematic approach to the integrated, simultaneous design of products and related processes, including manufacture and support. This includes consideration of manufacturing cost, quality control, production scheduling, marketing (including packaging), point of sale, user requirements, disposal, recycling, remanufacture and disassembly characteristics. The objective of concurrent engineering is the simultaneous consideration of the life-cycle impacts during preliminary system design, along with the immediate considerations of functionality. The relationship of these characteristics within the product development life-cycle are further identified in Fig. 3.

Figure 3 represents a general (high level) IDEF0 representation of three major processes of the PDLC. The activities are represented in the boxes. These include the performance of engineering and design, the manufacture of the product and the maintenance/disposal of the product after it reaches the market. The arrows going into the boxes in IDEF0 represent the inputs into the process that will be transformed. For example, material (raw, recycled, etc.) will be needed for the manufacturing activity. The arrows going into the tops of the activity boxes represent controls or constraints on the process. The customer and environmental requirements should be explicitly considered when designing the product. The outputs are arrows that come out of the right-hand side of the activity box. The product is an output of the manufacturing phase, as well as product waste. This waste will hopefully be reclaimed at the next stage, to be used again. The arrows going into the bottom of the boxes represent mechanisms that will be able to carry out the activity. The mechanisms are usually the tools, personnel and equipment necessary to carry out the transformation. The inputs, controls, outputs and mechanisms are defined as ICOMs.

Another characteristic of the IDEF0 modeling technique is its decompositional relationship among processes and ICOMs at various levels of detail. We do not show the decompositions in Fig. 3, but some of the subprocesses are listed in the columns below the boxes. For example, the 'Perform Engineering' activity consists of performing design, process, quality, test, support and environmental engineering, where each of these subactivities would be integrated through various sets of ICOMs. This is a powerful tool, since it allows for activity and waste-stream analysis at various aggregated levels.

The traditional view of the product life-cycle is that planning for the product is no longer important once it leaves the shipping dock. The new truth is that manufacturers should be aware of, and plan for, the product long after its delivery and distribution. This would include such issues as field maintenance and disposal of the product, along with the major ECM strategies. There is a need for research into the use of IDEF and other integrated structured methodologies to help in the evaluation of the product life-cycle, including product retirement. Development of standard and generic PDLC processes for various products can help a number of organizations develop their own specific models, especially those organizations that

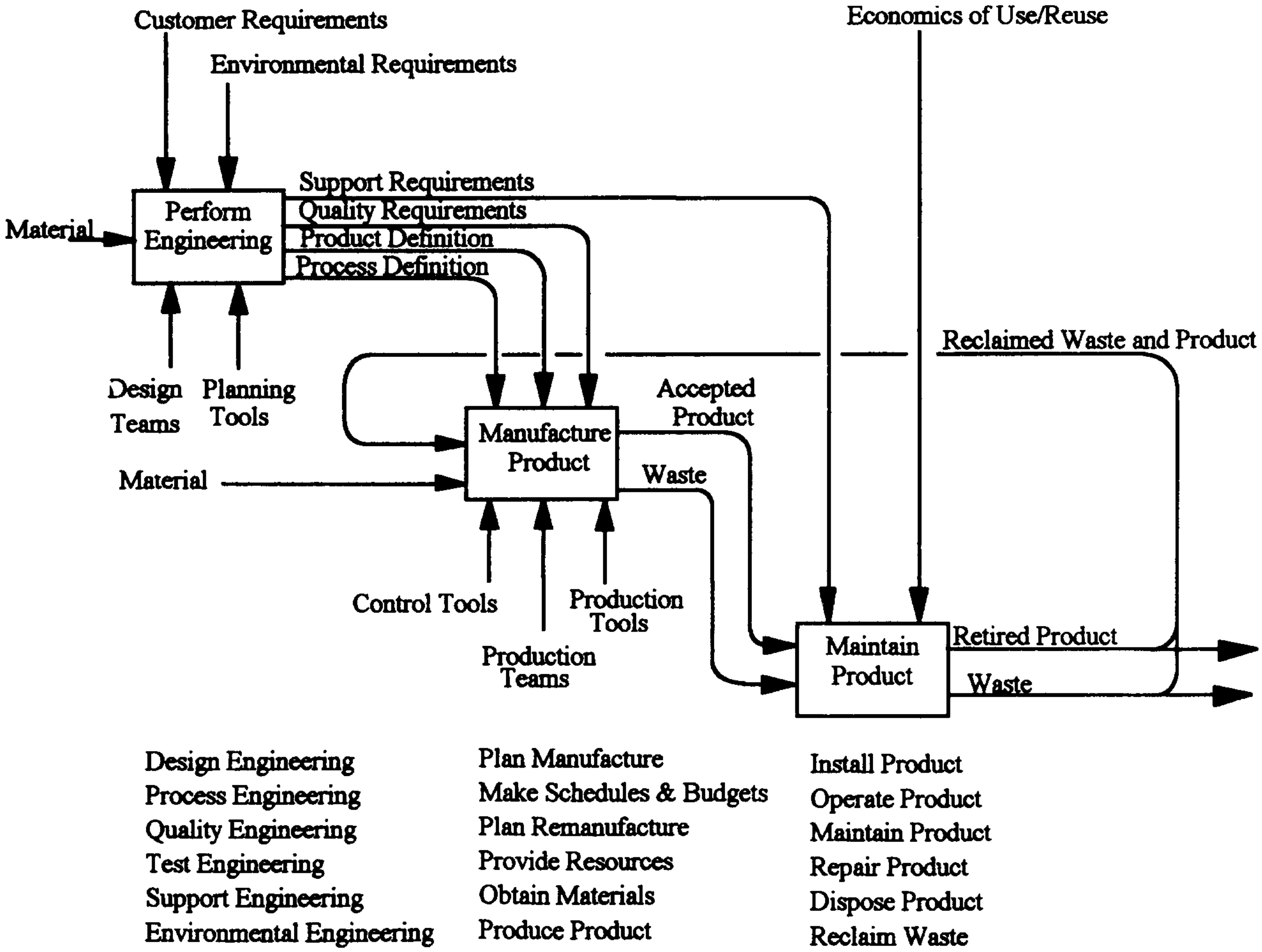

Fig 3 High level IDEF0 representation of product development life-cycle model

have limited resources. Additionally, the role of these methodologies in developing business processes and practices that will help in designing for the environment need to be determined. Currently, there has been little focus on using these structured methodologies to help in the analysis of ECM processes, products and technologies and their relation to each of the strategies.

4. ECM strategies

The Rs of environmental reform have become well known to industry: reduce, remanufacture, and reuse/recycle. They all deal with actual environmental impact, not just with evidence visible to the general public. These ECM strategies each have characteristics that will link to the basic process, product and technology components of manufacturing strategy. The related current and emerging issues associated with these linkages are summarized at the end of Section 4.

4.1 Reduction

Reduction, or waste minimization, is a strategy that has been driven by both organizational and external objectives. Waste minimization is a policy that has specifically been mandated by the US Congress in the 1994 Hazardous and Solid Wastes Amendments of the Resource Recovery Act (RCRA). Regulations from the Comprehensive Environmental Response, Compensation and Liabilities Act (CERCLA or the superfund) have made waste minimization strategies even more attractive [35].

The major emphasis in waste minimization is on source reduction or pollution prevention. Source reduction as defined by the federal pollution prevention act [36] includes approaches (products, processes and technology) that will reduce in-process waste streams. It does not include any approaches that are considered 'end-of-pipe', or after production techniques. This includes waste management, recycling/reuse, and remanufacturing approaches. Practices that can be considered source reduction activities include [36, 37]:

- input changes;
- operational improvement, such as loss prevention;
- production process changes;
- product reformulation;
- inventory control;
- administrative/organizational activities such as training.

Reduction of wastes in the waste stream is one strategy that links closely with the process and philosophies associated with just-in-time (JIT) manufacturing and total quality management (TQM). The role of TQM in ECM practices has been discussed by a number of authors and practised by a number of organizations [38, 39]. The elimination of wastes and continuous improvement are basic tenets of the TQM philosophy. Some of the relationships of quality at the source and defect reduction have direct implications on total waste reduction. Reduction in scrap has a direct relationship with minimizing the waste of a system; reduction in defects which require rework is a more indirect relationship. That is, less rework means less energy consumption. There are a number of TQM tools that can be used at various levels of analysis that help in the minimization of waste. TQM has elements such as early quality management through such strategic practices and tools as concurrent engineering. Concurrency is meant to integrate the design process to both marketing and manufacturing. One of the more useful tools that can be utilized to carry out this strategy is quality function deployment. Typically, this tool has been utilized to link customer with design requirements [40]; it should also be utilized to design various process requirements. A tactical goal and strategy in TQM (and JIT) is simplifying the designs of products (usually measured by levels in the bills of materials). Not only does this lessen the variety of items in the inventory, but it may also mean that less work, energy and time is associated with each level. Use of statistical process control is a tool that can be used at the operational level to control process defects.

It has also been shown that from a continuous improvement objective, companies that have achieved environmental excellence use continual benchmarking and do not deviate from goals [2]. Empirical studies that study the relationship between waste minimization success and TQM implementation need to be carried out.

We focused on TQM in the waste reduction process because TQM is one of the more important relationships between a manufacturing related philosophy and strategy and waste minimization. It also has dimensions that focus on product, process and technology related strategies. A number of more general research issues can also be identified for companies that wish to pursue an ECM strategy that includes reduction of waste. Some of these include:

- development of technology and processes that will perform additive fabrication (instead of subtractive);
- development and use of information technologies and systems and databases that will help identify substitutability of materials, where more hazardous, or waste-producing materials may be substitutable (these materials include those that are to be processed and those that are used to process other materials such as solvents [41]);

- development of waste monitoring processes and technology to minimize leakage into the environment;
- determination of various training programs for waste reduction and elimination;
- development of methodologies for assessing progress in pollution prevention which occurs as a result of actions or decisions made during the design stage of a product's lifecycle.

4.2 Remanufacturing

Remanufacturing refers to the repair, rework, or refurbishment of components and equipment to be held in inventory for either external sale or internal use. In a typical remanufacturing process, identical 'cores' (the worn-out components and equipment) are grouped into production batches, completely disassembled, and thoroughly cleaned. These parts are replaced at least back to the level of the product when new. The product is assembled, finished, tested, packaged, and distributed in the same manner as new products [42].

Remanufacturing has a number of implications related to its use in an ECM environment. Basically it relates to the ability of manufacturing firms to recycle their components. Yet remanufacturing has received less intense analysis and attention in firms than the original equipment manufacturing aspect itself. Part of this has to do with the stigma attached to refurbished goods, and the lack of standards, and consumer regulation laws stipulating the use of virgin materials [43]. Remanufacturing has also received limited analysis by academic manufacturing and operations researchers. There have been some issues that have been addressed in this field, but they have focused primarily on inventory control issues in remanufacturing environments [44–47].

Lund [42] and Garvin [48] describe some of the differences between regular manufacturing and original equipment manufacturing, as well as the product requirements that would lend a product to remanufacturing:

The major differences between manufacturing and remanufacturing arise as a consequence of using worn-out, discarded, or defective products as primary materials source. This factor affects not only the production process employed but also the contractual relationship with customers, who are also suppliers. The incoming material is known to be defective in some way. The production of reliable products from parts of unknown quality is one of the greatest tests of a remanufacturer's skills.

Criteria that distinguish products that lend themselves to manufacturing include:

(a) the product technology is stable;
(b) the process technology is stable;
(c) the product is one that fails functionally rather than by dissolution or dissipation;
(d) the product has a 'core' that can be the basis of the restored product;
(e) a continuing supply of such cores is available;
(f) the core is capable of being disassembled and of being restored to its original condition;
(g) the product is one that is factory-built rather than field-assembled; and
(h) the recoverable value added in the core is high relative to both its market value and to its original cost.

The remanufacturing process basically includes the disassembly of components, inspection and testing of the remanufacturable components, incorporation of any new improvements, and reassembly of components with newer systems.

Some general research questions and issues pertaining to remanufacturing and its relationship to ECM need to be addressed. These questions include:

- What are the financial and economic considerations and consequences of implementing a remanufacturing strategy?
- What are the technological planning, control and processing requirements of a remanufacturing environment and how do they compare with a standard manufacturing environment?

- What are the needs and what needs to be developed in terms of special tooling and manufacturing technology for disassembly in the remanufacturing process?
- What are the organizational (cultural, policy and infrastructure) requirements?
- Why is there a lack of utilization and consideration of this strategy by manufacturing enterprises?
- Is it more likely that a firm that has envisioned environmentally conscious manufacturing would focus a significant amount of its resources on looking into remanufacturing issues?
- What approaches exist and need to be developed to design, analyze, model and optimize the planning, management, control and operations of a remanufacturing shop, plant or production line?
- When is it cost effective and feasible to remanufacture a product and what type of economic models exist to help make that decision?

4.3 Recycling and reuse

A number of raw materials can be recycled. Solid wastes materials, including paper, glass, plastics and metals, are currently very abundant with an increasing amount every year being stored in landfills. Over 100 million tons of non-perishable waste is being buried in landfills every year, with at least 78 million tons of these wastes being made up of recyclable materials. This includes 50 million tons of paper, 12 million tons of glass, 11 million tons of plastics and 5 million tons of aluminum [49].

There is opportunity here to take materials that have been discarded from manufactured products and recycle them into virgin material that may be used again in manufacturing processes. Currently, numerous facilities exist outside a manufacturing organization that are able to provide recycled material for manufacturing purposes. From an environmentally conscious procurement practice, selection processes for suppliers and vendors should include the criterion of being able to supply environmentally conscious products, especially from the perspective of recycled material.

An intraorganizational ECM practice would be to incorporate into the manufacturing process plant equipment that can carry out recycling of products. Work stations that can take recyclable waste material and convert them to virgin material may require a substantial investment, but incorporating a recycling station may include numerous benefits and cost savings to a manufacturing enterprise. For example, a glass processing machine that turns old bottles into a substitute for virgin material may cost close to half a million dollars, but it also adds \$50–70 per ton to the value of the reprocessed product [49]. The refinement and eventual use of the recycled material will clearly impact the amount of investment and processing required. There are numerous strategies for the reprocessing and recycling of materials that may also require various process and economic considerations. Categories for recycling of manufactured products include [49]:

- retaining all properties embodied in the original product, where the characteristics of the product are used again in the manufacturing process and the source of the materials is completely from the recycled material, e.g. glass bottles being manufactured again as glass bottles (reusability level);
- recycling of wastes into alternative products, i.e. products manufactured from recycled and raw material, e.g. making fibreglass from glass bottles;
- processing of recycled material into products that are not usually made of the material, where all properties of the original product are all lost, e.g. glass to glassphalt.

Manufacturing enterprises may face other implications from a recycling strategy not only in the manufacturing function, but other functions throughout the enterprise as well [50, 51].

The linkage between recycling and reuse can be defined by the amount of treatment required; minimal treatment of a material is more closely associated with reuse of a product, while a material that requires a large amount of treatment can be considered to have undergone recycling. Reuse involves the on-site or off-site use, with or without treatment, of a waste. Reuse generally refers to the introduction of waste directly to a process in place of the normal raw material. The axiom that one group's waste is another's treasure can be utilized effectively from a reuse perspective. The necessary materials for various processes within an organization (or even among organizations) can be researched to determine whether various wastes can be utilized in the system, with little additional processing. This has been defined as a 'waste exchange' approach [52]. There are a number of other operations/manufacturing issues that pertain to the recycle/reuse ECM strategy. Some of these include:

- research into how manufacturers can alter the design of a product for increased reusability and recyclability;
- research into the product and material characteristics that will increase the recycling and reuse of products/materials;
- research into how a manufacturing system needs to be altered to incorporate equipment and technology for recycling and reusability;
- development of a system that will help trace, record and access recyclable and reusable, substitute products/materials and their sources.

These and other issues relating to ECM strategies and life-cycle assessment, and various relationships to product, process and technology strategies dealing with manufacturing and operations, are presented in Table 2. Table 2 is not meant to be exhaustive, but shows many of the major research, development and needs issues along the two dimensions.

5. ECM project planning and management

Part of the issue of product, process and technology development is the planning for, and adoption and implementation of, these programs. As we have argued throughout this paper, the issue of justifying and adopting ECM programs necessarily follows a strategy-driven approach. The major steps of one such general methodology are shown in Fig. 4. There, five interrelated steps are identified: strategic planning, enterprise assessment, strategic justification, implementation and audit.

In this process the initial phase consists of strategic planning at the corporate and strategic levels. This is a top–down planning process that is driven by the corporate mission, vision and strategic plans. The process for developing a strategic plan should consider the external opportunities and threats and relate these external factors to the firm's strengths and weaknesses. As discussed, the role of environmental and ecological strategies should be explicitly stated and maintained within the enterprise strategic plan. These plans should be operationalized to be able to carry out an assessment of the enterprise. This will require an assessment in various functional areas. The focus on the manufacturing function in ECM should not exclude other functional assessments. This integrated focus is necessary from both a life-cycle and a strategic perspective.

The assessment will help determine the need and configurations of ECM technologies. This analysis will require what has been defined as the 'As-Is' enterprise environment. Specific emphasis on environmental factors needs to include the development of environmental performance metrics and measures. The development and adoption of these measurements and metrics will be necessary for measurement of success and for continual improvement in the area of ECM. The determination of the appropriate metrics will be necessary in later stages, especially when seeking to justify, evaluate and eventually audit the various technologies. A number of performance metrics exist for various elements of the manufacturing and related functions [53, 54]. Selection of appropriate performance measures is important, since the optimization of the systems will rely on these performance measures. The selection of appropriate performance measures must have a direct relationship to

TABLE 2 Relationship of various issues facing ECM strategies and product, process and technology categorizations of general manufacturing strategies

ECM related strategies	General manufacturing strategies		
	Product	Process	Technology
Life-cycle issues	Design for the environment Inclusion of waste stream elements in product design Product/material standards data and availability Research and develop product environmental metrics	Determination of tangible and intangible costs and benefits for assessment data Development and use of structural modeling approaches for analysis Development and use of life-cycle analysis standards Maintain equipment for energy efficiency	Information technology for accessing data of various materials and products that have had life-cycle assessments Decision support systems development Need for design tool modifications Develop/adjust concurrent design technology Develop/use energy efficient technology
Reduction	Waste reduction in concurrent engineering and design Design to reduce defects and scrap Simplify bill of materials Use of TQM tools in design of product	Design of additive processes rather than subtractive ones Develop waste monitoring systems and performance measures Reduce inventory levels Integrate TQM practices, statistical process control	Develop manufacturing technology to support additive processes Develop information technology and data base to make substitutability decisions for materials Develop monitoring technology
Remanufacturing	Design for remanufacturability New product structure and bill of materials issues need to be developed Modular product design with interchangeable parts Determining design of products that include a number of components with remanufacturing characteristics	Disassembly processes need to be developed Production planning and control models for disassembly need to be studied Tools and techniques need to be developed for determination of when a product can be remanufactured Study/develop new inventory control practices	Develop manufacturing technology for separation and disassembly Technology for reliability testing of remanufacturable materials
Recycle/reuse	Design for recyclability and reusability Incorporation of recyclable material Incorporation of durable products/materials for reusability Product development issues to include secondary markets Modular product design with interchangeable parts Product packaging that is recyclable and minimal Develop recycling standards for various products	Develop recycling infrastructure requirements Integration of recycling equipment and technology into standard manufacturing process Building supplier network for recyclable materials Develop manufacturing plans, processes and control models for reusable/recyclable materials and products	Develop integrated manufacturing system technology with recycling stations Develop separation technology for recyclable and reusable material and products Research and develop information technology and network for access to sources of recyclable and reusable material Develop technology for disassembly needs Develop substitutable material that is recyclable and more durable for reusability

the strategy and objectives of the enterprise. Environmental performance criteria can be defined in a number of ways, adapting some of Sauer *et al.*'s [25] criteria. A listing for product, process and technology design criteria is shown in Table 3.

Most of these performance measures are relatively general and may serve as categories that

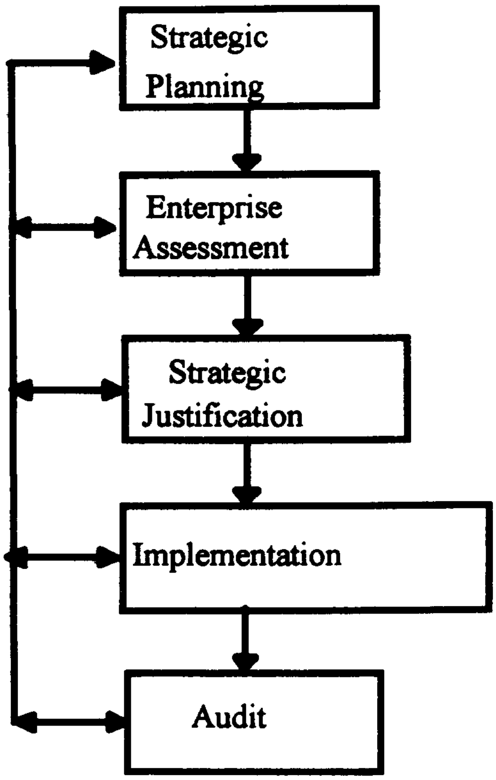

Fig. 4 A general (high level) strategic planning model for management of ECM projects and programs.

TABLE 3 A possible set of product and process development environmental performance measures

Recycled content	Water pollution
Recyclability	Soil pollution
Reusability	Air pollution
Remanufacturability	Noise pollution
Degradability	Resource/energy usage
Hazardous/toxic waste content	Regulatory compliance

can be disaggregated into lower level operational performance measures which can be used to manage the products and processes. These measures include easy-to-quantify and difficult-to-quantify measures. For most of these metrics appropriate measurement and estimation methodologies need to be derived.

As part of the assessment phase, some form of project or program assessment should be carried out to determine the needs of an enterprise. Example of approaches for specific use in assessing technology/project needs in an environmental setting include the use of technology logic diagrams [55] and material balancing approaches for technology evaluation [56]. Enterprise models, simulation tools, checklists and prioritization schemes may also be utilized for determination of various technology needs. More research in this area for various industries and technologies will be required for more accurate and complete assessments of factors associated with these needs.

For any ECM program to be seriously considered by management in a manufacturing enterprise, it must be justified. The issue of justification of strategic projects has usually focused on economic and financial justification. Consideration of these traditional factors alone cannot adequately evaluate and justify ECM technologies and practices [57, 58]. Typically, traditional financial models and criteria have focused on short-term tangible gains and have ignored more strategic and intangible benefits. A complete justification analysis of any ECM technology or project needs to consider the tangible, intangible and strategic factors. Research needs to be carried out in this area to determine the type of tangible, intangible, strategic and operational measures that exist and need to be developed, and how they may be integrated, to allow for a more complete evaluation of ECM technology and projects.

Another major issue facing justification of strategic ECM programs is the ability to determine costs and benefits associated with pursuing, or not pursuing, ECM strategies. Cost management systems must be developed that can provide useful information that can be utilized in life-cycle costing systems. A number of cost categories have been identified by the EPA that should be included in a total cost assessment [59]. The major categories include prevention, pollution (internal and external), appraisal, and future liability costs. There are a number of other manufacturing-process-related costs that can also be integrated with these costs. The difficulty lies in traditional cost management systems that do not have the capability to measure true costs associated with the actual activities that are carried out by a process, and are generally used for external financial reporting rather than internal management and control decisions [60]. To address this issue, the use of activity-based costing and management approaches have been recommended for data acquisition and justification procedures [61]. Only recently has there been a direct link with ABC, life-cycle costing and environmental measures [62]. There is ample research and application opportunity in this integral link.

Not only is the development of cost and performance data and other inputs required at the strategic justification stage, but there is also a requirement for the development of models that can utilize these data. The development of any models for the strategic justification of ECM systems will require consideration of multidimensional factors. A number of models that can simultaneously consider multiple dimensions of various strategic manufacturing technologies currently exist in the literature [63, 64]. Many of these models are very specific to various manufacturing characteristics. Yet few of them have specifically focused on justification of ECM related technologies. One such model is by Wilhelm *et al.* [65]. There is ample opportunity to adapt and apply these existing models and their characteristics for justification based on various environmental inputs and factors.

Implementation of ECM projects and programs is usually the most critical step in ensuring their success. This step includes all tasks necessary to take the system from design to an actual working system. This is the general term used to define the stage when the detailed designing and development of the ECM programs is initiated, as well as when actual implementation and operation of the system begins. This stage in itself is very dynamic and may require numerous iterations.

Unlike the previous phases in the ECM management cycle, where upper management involvement has played a major role in the decision-making process, at this stage upper management is only modestly involved. The planning and design now is the responsibility of a project team that should be composed of representatives from every function within the organization (i.e. an integrated resource management group). The steps in the implementation process include [66]:

1. acquisition and procurement;
2. operational planning;
3. implementation and installation;
4. integration.

The first three steps in this procedure can occur simultaneously, where all the stages require some sort of planning before beginning the actual process. Integration should also be planned, but knowing which operations and processes are needed, as well as the type of equipment that is to be acquired, is necessary before fully-fledged integration can take place.

This critical transition period also entails a number of dimensions. The implementation procedure must include training, testing, pilots, and integration steps. The role and relationships of legacy systems must be made very clear in the project plan. Various strategies do exist for the implementation phase, including phasing-in systems cut-over to new systems, parallel systems in operation at cut-over, and prototyping systems to full implementation. When implementing ECM technology, monitoring of the actual implementation should be continuous to guarantee that the initial performance of the systems achieves pollution-prevention requirements. Continuous monitoring after implementation should be made for data acquisition purposes.

The auditing process, which is usually one of the more neglected steps in any management and development system, should be carried out for a number of beneficial reasons. Clearly, auditing will help to identify whether or not the decisions made are meeting the expectations based on various environmental performance measures. The auditing process is the feedback process and should be utilized for the purpose of continuous improvement. It will also help in the identification of unexpected events or outcomes from the technologies implemented. This may require some form of updating to the various performance measures that were selected and the implications of the relationships among the performance measures. Setting up and maintaining an auditing system will also help in data acquisition and report generation that will reduce the probability of liability risk and regulatory penalties.

6. Summary and conclusions

What we have presented in this paper is a review of environmental initiatives on a global and domestic (US) scale that will impact the corporate and manufacturing strategy within a manufacturing enterprise. We have presented a number of ECM issues and strategies that need to be addressed by both practitioners/managers in manufacturing enterprises, and researchers in the field of manufacturing and operations management. A large number of relationships among general manufacturing strategy issues (product, process and technology) and ECM strategies (life-cycle analysis, reduction, remanufacturing, recycle/reuse) was identified. These issues overlap at a number of levels and dimensions with such topics as disassembly, design for 'X', materials and product development. A general model (and supporting tools) was used to help define a number of issues and opportunities relating to the strategic management and project planning of ECM projects and programs. There is extensive opportunity for research and initiatives in all the areas defined. Extension of the relationships to other manufacturing strategy dimensions such as location, capacity, etc., are issues that should also be addressed.

The paper's goal was to identify various issues, tools and goals related to ECM strategy. For organizations to be successful in an environmentally conscious competitive environment, the issues presented in this paper should be integrated into their policies and strategic directions.

References

1 T. Lent and R.P. Wells. Corporate environmental management survey shows shift from compliance to strategy. In: J. Willig (ed.), *Environmental TQM*. 2nd edn. McGraw-Hill, New York, pp. 7-32.

2 W.A. Wheeler. The revival in reverse manufacturing. *Journal of Business Strategy*, 13 (4) (1992) 8–13.

3 R.G. Schroeder and T.N. Lahn. Development of a manufacturing strategy: A proven process. In: J.E. Ettlie, M.C. Burstein and A. Fiegenbaum (eds.), *Manufacturing Strategy*. Kluwer, Boston, MA, 1990, pp. 3–14.

4 W. Skinner. Manufacturing – missing link in corporate strategy. *Harvard Business Review*, 47 (3) (1969) 136–145.

5 P.S. Adler. Technology strategy: A guide to the literatures. In: Richard S. Rosenbloom (ed.), *Research in Technological Innovation, Management and Policy. Vol. 4*. JAI Press, Greenwich, CT, 1989, pp. 25–151.

6 Samson. *Manufacturing and Operations Strategy*. Prentice Hall, Brunswick, Australia, 1991.

7 S.H. Weissman and J.C. Sekutowski. Environmentally conscious manufacturing. *AT&T Technical Journal*, 70 (6) (1991) 23–30.

8 M.E. Porter. *Competitive Strategy*. Free Press, New York, 1980.

9 R.D. Klassen. Integration of environmental issues into manufacturing. *Production and Inventory Management Journal*, 34 (1) (1993) 82–88.

10 J.A. Ottman. Green consumerism: the trend is your friend. *Directors & Boards*, 16 (4) (1992) 47–50.

11 G. Pinchot. The ecology of success. *Executive Excellence*, 9 (10) (1992) 7–8.

12 A.C. Hax and N.S. Majluf. *The Strategy Concept and Process: A Pragmatic Approach*. Prentice Hall, Englewood Cliffs, NJ 1991.

13 R.H. Hayes and S.C. Wheelwright. *Restoring Our Competitive Edge: Competing Through Manufacturing*. Wiley, New York, 1984.

14 T. Hill. *Manufacturing Strategy: Text and Cases*. Irwin, Homewood, IL, 1989.

15 J.A. Kirton. Implementing advanced manufacturing technology – the way it is. *Managing Advanced Technology. Proceedings of the UK Operations Management Association Conference*, January 1986. IFS Publications, Bedford, 1986, pp. 57–67.

16 J.R. Meredith. Implementing the automated factory. *Journal of Manufacturing Systems*, 6 (1), (1987) 1–13.

17 H. Noori. *Managing the Dynamics of New Technology*. Prentice-Hall, Englewood Cliffs, NJ, 1990.

18 J.F. Stahl. Manufacturing strategic planning: Key to

competitive strength. *CIM Review*, 6 (1) (1989) 14–20.
19 H. Inoue, Y. Nakazawa and N. Ohyama. ECOFACTORY: Concept and R&D Themes. Technical Paper, Mechanical Engineering Laboratory, Agency of Industrial Science and Technology, Ministry of International Trade and Industry, Japan, 1992.
20 MCC (Microelectronics and Computer Technology Corporation), *Environmental Consciousness: A Strategic Competitiveness Issue for the Electronics and Computer Industry*. Austin, TX, 1993.
21 G. Heaton, R.C. Repetto and R. Sobin. *Backs to the Future: US Government Policy toward Environmentally Critical Technology*. World Resources Institute, Washington, DC, 1992.
22 L. Matysiak. Design for recycling: A new corporate strategy in the automotive industry. *International Journal of Environmentally Conscious Design and Manufacturing*, 2 (16) (1993) 5–12.
23 A. Redd. World's first automobile disassembly plant. *Biocycle*, 33 (2) (1992) 82–83.
24 K. Fouhy. Life cycle analysis sets new priorities. *Chemical Engineering*, 100 (7) (1993) 30–34.
25 B.J. Sauer, R.G. Hunt and M.A. Franklin. *Background Document on Clean Products Research and Implementation*. Risk Reduction Engineering Laboratory, EPA, Cincinnati, OH, 1990.
26 B. Voss. The green marketplace. *Sales & Marketing Management*, 143 (8) (1991) 74–76.
27 S.D. Willits and R. Giuntini. Helping your company go green. *Management Accounting*, 75 (2) (1994) 43–47.
28 R.L. Bergland. *Quality Costs and Pollution Prevention. ASQC Quality Congress Transactions*, Milwaukee, WI, 1991, pp. 602–609.
29 G.A. Lorton, C.H. Fromm and H. Freeman. *The EPA Manual for Waste Minimization Opportunity Assessments*. US EPA, EPA/600/S2-88/025, Cincinnati, OH, 1988.
30 EPA. *Pollution Prevention Research Branch: Current Projects*. USEPA, Risk Reduction Engineering Laboratory, Cincinnati, OH, 1992.
31 J.D. Snyder. Manufacturing group seeks common strategy against environmental bugaboos. *Environment Today*, 2 (8) (1991) 3, 48.
32 J. Andrews. Fridge makers design for the future. *Custom Builder*, 7 (6) (1992) 98–100.
33 R. Babyak. Disassembly: Who will do it? *Appliance Manufacturer*, 39 (7) (1991) 68.
34 R.A. Frosch and N.E. Gallopoulos. Strategies for manufacturing. *Scientific American*, September, 1989, 144–152.
35 J.W. Tillman. *Achievements in Source Reduction and Recycling for Ten Industries in the United States*. EPA/600/2-91/051, Cincinnati, OH, 1991.
36 EPA. *Facility Pollution Prevention Guide*. USEPA, Office of Research and Development, EPA/600/R-92/088, Washington, DC, 1992.
37 V.A. Nusbaum. Are environmental and manufacturing objectives compatible? *Proceedings of the 1991 IEMT Symposium*, 1991, pp. 275–277.
38 T.S. Isbell. The backside of TQM: How waste indicates haste. *Industrial Engineering*, November 1991, pp. 42–45.
39 J. Willig. *Environmental TQM*. McGraw-Hill, New York, 1994.
40 J.L. Brossert, *Quality Function Deployment: A Practitioner's Approach*. ASQC Quality Press, Milwaukee, WI, 1991.
41 R.S. Buttner. Concepts in design for the environment. *3rd Annual RIOTECH ECM Workshop, Albuquerque, NM*, 1993.
42 R.T. Lund. Guidelines for an original equipment manufacturer starting a remanufacturing operation. Technical Paper, 1983.
43 D.M. McConocha and T.M. Speh. Remarketing: commercialization of remanufacturing technology. *Journal of Business and Industrial Marketing*, 6(1–2) (1991) 23–27.
44 P.C. Jordan. Effects of a dynamic lot-sizing method on return on investment. *Production and Inventory Management Journal*, 29 (1) (1988) 29–33.
45 B.D. Panisset. MRP II for repair/refurbish industries. *Production and Inventory Management Journal*, 29 (4) (1988) 12–15.
46 J.H. Perry. The impact of lot-size and production scheduling on inventory investment in a remanufacturing environment. *Production and Inventory Management Journal*, 32 (3) (1991) 41–45.
47 W. Wassweiler. Know the MRP II fundamentals that support remanufacturing. *Manufacturing Systems*, 11 (1) (1993) 52–55.
48 D.A. Garvin. *Operations Strategy: Text and Cases*. Prentice Hall, Englewood Cliffs, NJ, 1992.
49 C. Rennie and A. MacLean. *Salvaging the Future: Waste Based Production*. Institute for Local Self-Reliance, Washington, DC, 1989.
50 K. Hurst and G. Humphreys. *Manufacturing with Recyclables: Removing the Barriers*. Community Environmental Council, Gildea Resource Center, Santa Barbara, CA, 1993.

51 M. Lewis, T. Swope, T. Bhushnan, D.S. Sapon-Borson, T. Tallings and T. Martin. *Recycling Economic Development through Scrap-Based Manufacturing*. Institute for Local Self-Reliance, Washington, DC, 1994.
52 G. Vajda. Integrated waste minimization. *Manufacturing Systems*, 10 (1) (1992) 36–40.
53 T.D. Fry and J.F. Cox. Manufacturing performance: Local versus global measures. *Production and Inventory Management Journal*, 30 (2) (1989) 52–56.
54 B.H. Maskell. *Performance Measurement for World Class Manufacturing*. Productivity Press, Cambridge, MA, 1991.
55 R.F. Fellows. Technology logic diagrams and their use in the identification of technology needs. *Proceedings of the 2nd International Conference on Environmentally Conscious Manufacturing*, Arlington, VA, 1993.
56 EPA (Environmental Protection Agency), *Strategic Waste Minimization Initiative (SWAMI)*. USEPA, Office of Research and Development, Washington, DC, 1992.
57 National Research Council. *Frontiers in Chemical Engineering: Research Needs and Opportunities*. Board on Chemical Sciences and Technology. National Academy Press, Washington, DC, 1988.
58 S. Schmidheiny. Needed: New measures of competitiveness. *The World Competitiveness Reports 1991*. World Economic Forum, 1991, pp. 177–179.
59 EPA (Environmental Protection Agency). *Pollution Prevention Benefits Manual*. Washington, DC, 1990.
60 R.S. Kaplan. One cost system isn't enough. *Harvard Business Review*, 66 (1) (1988) 61–66.
61 R.S. Sawhney. An activity based approach for evaluating strategic investments in manufacturing companies. *Journal of Manufacturing Systems*, 10 (5), 1992, 353–365.
62 J.G. Krueze and G.E. Newell. ABC and life cycle costing for environmental expenditures. *Management Accounting*, 75 (2) (1994) 38–42.
63 A. Kulkarni and H.R. Parsaei. Economic justification of flexible manufacturing systems: A bibliometric analysis of the literature. In: H.R. Parsaei, T.L. Ward and W. Krawowski (eds.), *Justification Methods for Computer Integrated Manufacturing Systems*. Elsevier, Amsterdam, 1990, pp. 275–309.
64 Y.K. Son. A comprehensive bibliography on justification of advanced manufacturing technologies. *Engineering Economist*, 38 (1) (1992) 59–72.
65 M.R. Wilhelm, H.R. Parsaei, M. Fleischman, A. Kaltenhauser and J. Watters, Selection of waste management technologies to implement manufacturing pollution prevention strategies. *International Journal of Environmentally Conscious Design and Manufacturing*, 2 (2) (1993) 41–47.
66 J. Sarkis and L. Lin. An IDEF0 functional planning model for the strategic implementation of CIM-systems. *International Journal of Computer Integrated Manufacturing*, 7 (2) (1994) 100–115.
67 N. Gross. The green giant? It may be Japan. *Business Week*, 24 February (1992) 74–75.
68 C.N. Madu. *Management of New Technologies for Global Competitiveness*. Quorum Books, Westport, CT, 1993.

Joseph Sarkis is currently an Assistant Professor at the University of Texas at Arlington in the College of Business Administration. He earned his PhD from the State University of New York at Buffalo. His research interests include manufacturing strategy and management, and enterprise modeling. He has published papers in a number of academic journals and has made presentations and published at a number of national and international conferences. He is a member of the American Production and Inventory Control Society (APICS), The Institute of Management Sciences (TIMS), the Decision Sciences Institute (DSI), the Production and Operations Management Society (POMS), and the American Society for Engineering Management. He is also a certified production and inventory manager (CPIM). He is affiliated with the Automation and Robotics Research Institute at UTA and involved as a faculty associate with their Integrated Enterprise Frameworks group.