

Dave Allen

University of Texas, Austin
Austin, TX 78712

Diana Bauer

EPA
Washington, DC

Bert Bras¹

Georgia Tech
Atlanta, GA 30332

Tim Gutowski²

M.I.T.
Cambridge, MA 02139

Cindy Murphy²

University of Texas, Austin
Austin, TX 78712

Tom Piwonka

Univ. of Alabama
Tuscaloosa, AL 35487

Paul Sheng

McKinsey
Austin, TX 78712

John Sutherland

Michigan Tech
Houghton, MI 49931

Deborah Thurston

Univ. of Illinois, Urbana-Champaign
Urbana, IL 61801

Egon Wolff

Caterpillar
Peoria, IL 61629

Environmentally Benign Manufacturing: Trends in Europe, Japan, and the USA

In this paper, findings of the Panel for International Assessment of Environmentally Benign Manufacturing Technologies, sponsored by the United States National Science Foundation, are discussed. The mission of this interdisciplinary panel was to assess the international state-of-the-art in Environmentally Benign Manufacturing (EBM), and to identify priorities and collaborative opportunities. Over 50 sites in Japan, Europe and the United States were visited over the course of the yearlong study. This paper focuses on some global trends that were observed. [DOI: 10.1115/1.1505855]

1 Introduction

Among industrial activities in the US, the contribution of manufacturing to various environmental impacts is enormous. Taken collectively, manufacturing industries dominate in such areas as; 1) toxic chemicals, 2) waste, 3) energy, and 4) carbon emissions. Manufacturing is also a heavy user of water, and there have been many cases of air, water and soil contamination which have led to such actions as Superfund cleanups, class actions suits and a variety of other corporate liabilities. For example, among the industries selected by the EPA for toxic materials monitoring, manufacturing releases are larger than all other activities, with the one exception of metals mining, which is closely related to manufacturing. This is shown in Fig. 1, which gives the 1998 EPA Toxic Release Inventory (TRI) results by industrial categories [1]. This figure becomes even more significant when one realizes that the United States produces more waste than any other country in the world. This is true both on an absolute scale as well as a per capita scale [2]. Hence US manufacturing might be characterized as the most wasteful industrial activity, in the most wasteful nation.

The area of what is termed "Environmentally Benign Manufacturing" (EBM) in this paper addresses a central long-term di-

lemma for manufacturing; *how to achieve economic growth while protecting the environment*. The conflict is fundamental, rooted in part in the materials conversion process, which takes from the earth and gives to the customer, the stockholder, and to those who make a living or derive support from this enterprise, and in part in consumerism, which focuses on current needs often with disregard for the future. The resolution of this conflict is a serious issue for society to address, for in the near future it will threaten our well-being. The question then for the environmentally conscious manufacturer is how to incorporate both economy and environment into their business plan.

Once a firm is motivated to address environmental issues, *what then are the right things to do?* The answers are not simple. There are many aspects to this problem including; toxic materials, waste and wastewater, emissions and greenhouse gases, energy usage, and material and product recycling. Furthermore, at the root of all environmental issues are people; people with different values, goals and needs, and people from different generations. The development of an environmental strategy needs to address all of these issues and convey this understanding into an effective program of action.

These questions (and more) led the National Science Foundation, in cooperation with the Department of Energy, to fund a study through the World Technology Evaluation Consortium (WTEC) that would focus on evaluating the current efforts and state of the art in EBM in Europe, Japan, and the United States. A

¹Corresponding author.

²Panel co-chairs.

Contributed by the Manufacturing Engineering Division for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received August 2001; Revised January 2002. Associate Editor: J. Lee.

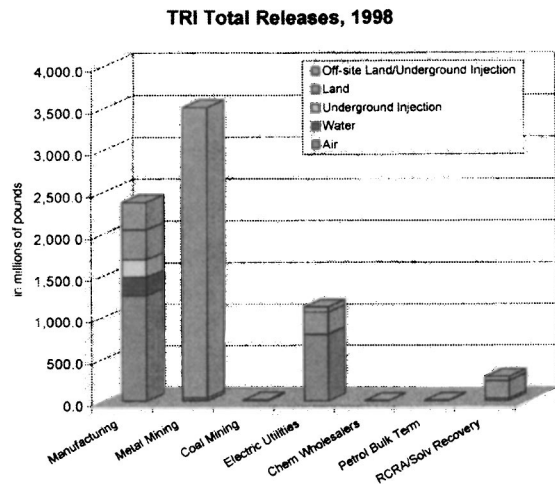


Fig. 1 EPA toxic release inventory releases for 1998 by category (EPA 1998a)

panel of 10 US experts from academia and industry was convened for this study. The panelists' task was to sort out these complex and intertwined issues, and to organize them in a way that is both understandable and inclusive. Often, the issues went far afield from the original engineering focus of the panelists. But the overwhelming importance of these broad issues requires that they be included here to accurately represent the nature of our findings.

The full report of our findings can be found in [3]. In this paper, we provide insight on some major global trends in some key areas. In particular, we will share some observations by region, crosscutting high-level systems issues, as well as industry specific findings. But first, some more details about the study is provided.

2 Description of the Study

The range of issues for EBM is quite large. To make the panel's mission manageable, the focus was placed primarily on manufacturing processes (including design) with an emphasis on metals processing and polymer processing. Two key application areas were identified, automotive and electronics.

The panel began with technology roadmaps for steel, aluminum, casting, electronics, automotive, polymers and composites. One of the goals was to benchmark global trends. In addition to the US, Japan and Europe were chosen as sites, in part because they both have a high population density and a high per capita Gross Domestic Product—two critical factors that generally indicate both the potential for environmental problems and the resources to address them. Europe and Japan are also known for their international leadership in environmental issues.

At each of the foreign locations the panel visited a mix of sites including governmental agencies and laboratories, academic institutions and companies. In the United States visits focused exclusively on companies. The goals for each site visit were to 1) advance the understanding of environmentally benign manufacturing, 2) establish a baseline and to document best practices in environmentally benign manufacturing, 3) promote international cooperation and 4) identify research opportunities. A total of 52 different locations were visited in Japan, Europe and the US as listed in Tables 1, 2 and 3.

3 Regional Observations

One of the goals of this study was to benchmark and compare trends in Japan, Europe and the US. The motivation for doing this was to understand how well the US is performing in the area of environmentally benign manufacturing relative to Europe and Japan in the areas of research and development, industrial strategies and priorities, governmental policies and regulations, and educational activities. A key finding was that cultural, geographic, and

Table 1 Japanese sites visited

Fuji Xerox	NIRE
Hitachi PERL	New Earth Conference & Exhibition
HORIBA LTD.	NRIM
Kubota	PVC Industrial Association
MITI/Mechanical Engineering Lab.	Sony Corporation
MITI/AIST/NOMC	Tokyo Seikan Kaisha
Nagoya University	Toyota Motor Corporation
NEC Corporation	University of Tokyo
Nippon Steel Corporation	Institute for Industrial Science

Table 2 European sites visited (Belgium, Denmark, Netherlands, Germany, Sweden, Switzerland)

Corus Holland	ICAST
DaimlerChrysler	IVF
Denmark Tech. U.	MIREC
EC Environmental Directorate	Siemens
EC Research & Technical Development	TU Aachen
Excello	TU Berlin
Fraunhofer, Aachen	TU Delft (Ministry of Environment, Lucent
Fraunhofer, Berling	Technologies, Philips Consumer Electronics)
Fraunhofer, Stuttgart	University of Stuttgart
	Volvo

Table 3 United States sites visited

Applied Materials	GM
Caterpillar	IBM
CERP	Interface
Chaparral Steel/Cement	Johnson Controls
Daimler Chrysler	MBA Polymers
Corus Tuscaloosa	Metrics Workshop
DuPont	Micro Metallics
Federal Mogul	NCMS
Ford	

business needs strongly influenced the focus areas in each of these regions, making direct comparisons rather challenging. At a technical level, the tendency that was noted for each of the regions was as follows.

- The US appears to be most heavily involved in materials and processes and in avoiding litigation.
- Japan is focused on applications that incorporate EBM into their business strategies, introduction of new products (primarily to gain market share), and resource conservation.
- Europe is heavily concerned with product end-of-life, infrastructure (supply chain and reverse logistics), elimination of materials of concern, and systems level modeling.

In the following, we discuss these observations in more detail.

3.1 United States. Most of the EBM focus in the US is on materials and processes within the traditional manufacturing environment. This may be viewed as a logical response to media-based regulations and policy since these areas and activities most directly affect air, water, and solid waste. The automotive industry has concentrated on the materials and processes used in structural metals and for paint application; the electronics industry has concerns over a number of materials and processes. However, where there are market drivers that encourage consideration of products and end-of-life solutions, there are activities in US industries within these areas as well. For example, large international firms such as Ford and IBM are responding aggressively to European Union (EU) directives (specifically the Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicle (ELV) Directive). Ford has designed a car specifically for European take-back. IBM has a strong electronics products recycling effort and has produced a computer using 100% recycled plastic housing.

Metrics and supply chain management are of concern in the US but not nearly to the degree that was observed in Europe. In addition, the motivation appears to be different. Often it can be linked to concern over potential future liability (especially with large chemical and electronics companies) or in response to a customer (such as Johnson Controls responding to the automakers). However, there are some exceptions. Within large companies (e.g., DuPont, Ford, IBM, AT&T, HP) there are typically small groups that are very focused on systems level environmental issues. In addition, there are some smaller companies that view a systems level approach to managing environmental issues a key strategy, such as Interface, Inc.

Kalundborg, Denmark, is recognized as the premier site in the world for material exchanges, however there is also significant interest and activity in the US in this area. Of note are the activities that are occurring at TXU's Chaparral Steel. Cornell University's Work and Environment Initiative also focuses on eco-industrial park development. At Red Hill, MS, a power plant is being built directly next to a lignite mine. Since virtually all transportation costs are thus eliminated, this will allow a marginally economic, low-grade of coal to be used. In addition, a nursery grower plans to build greenhouses to make use of waste heat from the power plant. The US Department of Energy (DOE) is working in cooperation with the Polymer Alliance Zone of West Virginia to establish an eco-industrial park in Parkersburg, WV, with a focus on recycling of electronics. Similar efforts are underway in Austin, TX (funded by the Department of Commerce, EDA) and in Broome County, NY (the Aurora Project, backed in part by IBM).

Recycling efforts in the US are subject to the free-market with variable results. (Note that for the purposes of this study, the discussion of recycling efforts is limited to engineered metals and polymers and to automotive and electronic applications). The US continues to be the largest producer of solid waste, even when normalized (Fig. 2). However, until land-fill space and/or costs become critical, as they have in Japan and Europe, it may be difficult to develop viable material recycling processes, except where there is clear economic advantage (such as for steel, aluminum, and precious/base metals). There are significant efforts in the

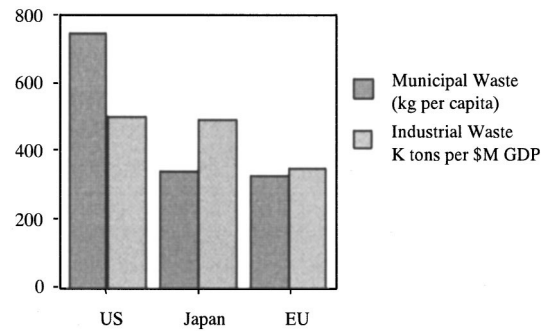


Fig. 2 1990 per capita waste for US, Japan and EU (Park and Labys, 1998)

US to recycle certain polymers. DuPont had a pilot facility to recycle polyester and MBA Polymers is developing methods for recovering engineering thermoplastics such as acrylonitrile butadiene styrene (ABS) and polycarbonate (PC). However, the economics of both of these facilities was or is a challenge. In all cases within the US, companies must rely on their own initiative to collect and consolidate materials, to recover materials in a cost-effective manner, and to find markets for their output streams.

There is a much greater effort at the research and development level to investigate the recycling of engineering thermoplastics that are a predominant material in both electronics and automotive applications. Perhaps this is because incineration is not as acceptable an option in the US as it appears to be in Japan and Europe. The Society of Plastics Engineers (SPE) holds an annual conference with a very strong emphasis on separation and recovery technologies. Options include separation by hydrocyclone (used by MBA Polymers in California and Butler-MacDonald in Indianapolis) and electrostatic properties, with systems available from US companies such as Carpc and the German company Hamos.

3.2 Europe. In Europe, the European Union is concerned primarily with product end-of-life, infrastructure (supply chain and reverse logistics), elimination of materials of concern, and systems level modeling. This is in large part made possible by their insular nature, with the majority of imports and exports being between EU Member States. Take-back infrastructure is especially well developed in the Netherlands, as seen at MIREC, and other countries are expected to develop similar programs in the near future. These efforts are being driven in large part by the Waste Electrical and Electronic Equipment (WEEE) and by the End-of-Life Vehicle (ELV) directives.

Europe is also a world leader in the area of life cycle assessment (LCA). A good reference to LCA can be found at the European Environment Agency (EEA) website (<http://org.eea.eu.int>). There are a number of documents available that discuss incorporation of LCA into business practices [4,5]. Arguably, DFE/LCA software tools were first introduced in the United Kingdom (Boustead) and France (Ecobalance). TU Delft, in cooperation with Philips Electronics and other groups in The Netherlands, has also done a significant amount of work in this area. So has TU Denmark with Danish industries. Germany also has had significant LCA developments and collaborations between various German universities and companies.

In general, there was evidence of more collaborative relationships between government, industry, and universities in the European countries we visited. Certainly, there seems to be more attempts at using "carrots" rather than "sticks." And while some of the policies are met with skepticism, and sometimes even downright refusal to cooperate, the governments appear to offer more room for post-policy negotiation than in the US.

One interesting trend is the introduction of environmental taxes by Member States on environmentally harmful products and activities [6]. While the shifts have been small and the bulk of the revenue is from energy taxes, including transport fuels that make

up more than three-quarters of energy taxes, there are clear indications that this is an increasing trend. In 1980, 5.84% of the total revenue was derived from environmental taxes. This number had increased to 6.17% in 1990 and to 6.71% by 1997 [7]. The tax base is also being broadened from “polluter pays” to the more comprehensive “user pays.” For example, there are taxes on groundwater extraction in France, Germany, and the Netherlands. In addition to directly penalizing undesirable behaviors, it is hoped that these taxes will provide some level of social engineering and increase general awareness of environmental issues.

3.3 Japan. In the traditional manufacturing environment, Japan is focused on applications and products and technical solutions tend to be at the operations level. One example of this is Toyo Seikan’s waste minimization program and use of pre-coated steel in the manufacture of beverage cans. There is also evidence of early adoption of emerging (non-Japanese) technologies in new products; for example, Honda, and Toyota were the first to introduce hybrid cars and Sony and Hitachi manufacture a significant volume of printed wiring boards that use micro-via interconnect and bromine-free flame retardants. The manufacture of vinyl window frames using triple co-extrusion with a recycled PVC core demonstrates an innovative application of existing materials and equipment. Progressive implementation of technology was evident with the use of plastic as a reducing agent (also done in Germany).

As a country that relies heavily on marketing high value-added consumer products to countries all over the world, Japanese industry must be highly responsive to global policies. The most striking example of this is the strong emphasis on ISO 14000, which was seen advertised in public areas, including mass transit systems. Japanese electronics companies were the first to develop lead-free solders and offer bromine-free printed wiring boards in response to the EU’s WEEE Directive. Japan’s limited amount of natural resources and limited landfill space evokes a strong awareness of the relationship between conservation and economics (lean=green), as observed at Toyota and Toyo Seikan. Toyota claims that their highly efficient assembly line at Tsutsumi produces only 18 kg landfill waste per automobile. Fuji Xerox has a very well implemented program of component reuse.

Of the three regions studied, Japan appears to have the greatest concern with CO₂ emissions and global warming. CO₂ emissions are measured as a function of energy consumption, and since Japan has extremely high energy costs, there is clear economic incentive as well as environmental incentive to be concerned with this issue. However, given that most of Japan’s populace lives at or near sea-level, there may be concern over rising sea-levels as well.

Japan demonstrates a strong alignment of internal resources not seen in the other two regions. This manifests itself as a unified response to EBM and is evident in the areas of public education, environmental leadership, and consensus building. There is also a commitment to public development of data and software tools such as their national LCA (Life Cycle Assessment) project. In this effort the Japanese government is trying to develop a large LCA database that is specific to Japan and which is viewed as a national project. Hitachi was particularly outspoken in their strong interest in systems integration.

The emphasis on recycling in Japan is between that of the US and the Europe. Government is invested in developing infrastructure for recycling (e.g., PVC from construction sites) and industry is beginning to establish standards for recycled materials, such as PVC for non-pressurized waste water pipes.

4 EBM Drivers and Motivators

Table 4 lists the motivating factors for interest in environmentally benign manufacturing that were observed. Early regulatory mandates focused on control of emissions, employing a media-based (air, water and solid waste) approach. Manufacturers’ early efforts in environmentally conscious behavior was thus focused

Table 4 Motivating factors for EBM

Regulatory Mandates
Emissions standards (air, water, solid waste) Worker exposure standards Product take-back requirements, banned materials
Competitive Economic Advantage
Waste Treatment and Disposal (\$170 billion/year in U.S.) Resource consumption and costs - Energy, Water, Materials First to achieve cost-effective product take-back system, reduced liability
Green Marketing
Corporate Image ISO 14001 EPA Toxic Release Inventory (TRI) Market Value of Company Dow Jones Sustainability Group Index Investor Responsibility Research Center Eco-labeling, employee satisfaction

on “end-of-pipe” treatment and waste disposal systems. Similarly, worker exposure motivated point-of-contact worker protection systems, which prevented or minimized worker exposure to harmful materials and/or processes. A new trend is product take-back legislation, which places the logistic and economic burden of product disposal on the manufacturer. The Dutch have recently enacted this and the European Union is expected to follow soon.

Economic forces further motivate pro-active EBM behavior beyond simple regulatory compliance. One consistent theme the panel observed was interest in the correlation between environmentally benign manufacturing technologies and economic efficiency. At several site visits, the host stressed that the EBM technology they developed was also more profitable. This is accomplished in several ways. First, if “end-of-pipe” emissions can be decreased, significant savings in waste treatment and disposal costs can be realized. The “Pollution Prevention Pays” program at the 3M company sought to exploit such opportunities. U.S. manufacturers currently spend approximately \$170 billion per year in waste treatment and disposal costs.

Some manufacturers have realized that products and processes that generate large amounts of waste are, by definition, inefficient and costly. Many EBM technologies consume less raw materials and/or energy, resulting in simultaneous environmental protection and cost savings. In other words, “lean=green.” While this is extremely promising, it is also a much more complex “concurrent engineering” problem than simply treating waste at the “end of pipe” in response to regulations. It requires thoughtful analysis long before the manufacturing process begins, and even long before the product is designed. Another economic motivator is that the manufacturer that is first to develop a cost-effective product or system that complies with anticipated product tack-back legislation will have a competitive advantage in the marketplace, as well as an enhanced corporate image.

Beyond the immediate economics of the manufacturing process, larger scale marketing considerations also motivate EBM. Factors cited by leading EBM manufacturers include the importance of maintaining an environmentally responsible corporate image (e.g., Volvo), high-level directives from a corporate leader (e.g., NEC, Interface) and customer demand (e.g., Siemens). The regulatory complexities of an increasingly global economy have motivated several EBM leaders to define their own pro-active environmental goals that go far beyond minimum compliance with

varying local regulations. Another motivating factor is investors. The correlation between the market value of the company and its environmental management program is only beginning to be studied, but several groups have begun gathering data to help identify companies that emphasize social responsibility, such as the Dow Jones Sustainability Group Index, and the Investor Responsibility Research Center. Initial analyses indicate a correlation between social responsibility and long term profitability.

5 Crosscutting Systems Level Issues

Because of the intricate interplay between regulatory, technical, economic and other factors, environmentally benign manufacturing requires a systems level approach. As many hosts told us, technological competence and good intentions alone do not assure success; a systems approach is essential. For example, Volvo succeeded in developing and implementing technology for "the world's cleanest paint line," utilizing water-based chemistry. However, rising energy prices forced a more comprehensive systems analysis, which revealed that the cost and environmental impact resulting from the "clean" paint line's energy consumption arguably outweighed the decrease in paint line emissions. Another example is the failure of German recyclers who, although technologically competent, were financially unsuccessful because the enactment of product take-back regulations came too late to provide feedstock. Lessons learned include the necessity of including all environmental impacts in the analysis, including those of energy consumption, energy costs, timing and location of regulations.

During our visits, we recognized a number of key crosscutting system level approaches, which are discussed next.

5.1 Product-Take Back and Recycling. One of the best examples of a "systems approach" is product take back and recycling operations. Here many elements of an inter-connected system must be put into place and coordinated in order for success. Clearly, the Dutch initiatives in requiring product take-back and recycling systems in order to reduce landfill have demonstrated that it is possible to implement a working take-back system for electronics. Furthermore, the European Commission legislation on electronics take-back will most likely follow the Dutch model, except they are expected to be stricter, for example including medical equipment. Hence, in Europe, it was observed that manufacturers no longer question the issue of product take-back, but rather are focusing their energies on how to achieve the best approach. Japanese manufacturers are similarly focused on cost-effective compliance with pending European, as well as Japanese take-back legislation. While the Japanese are perhaps even more space-limited in general than the Europeans, their primary motivation appears to be European legislation, since that is a large portion of their market.

Lessons learned are that a successful take-back system must be rooted in an economically viable approach to be self-sustaining. For example, MIREC (an electronics recycler) recommends finding markets for materials first, then recycle. A successful system also requires cooperation between many stakeholders, including the government, communities, consumers, manufacturers, and recyclers.

The Dutch also learned that consumers did not object to paying a "disposal fee" at point of purchase. A 25 Guilder fee (approximately \$10) on a \$300 refrigerator or TV did not appear to affect consumers purchasing decisions. One reason cited was that it was a relatively small increase compared to the cost of the product. Furthermore, the fee was levied on all products, hence, no competitive disadvantage was created.

Regarding the recycling process itself, it was observed that state-of-the-art reprocessing is still highly dependent on low-skilled manual labor (for sorting, disassembly, inspection). As such, the recycling/reuse industry is also seen as an opportunity to create new jobs to lower unemployment, especially in Germany. The US appears to lead in mechanical separation technologies (see, e.g., MBA Polymers).

There are several difficulties encountered when developing a product take-back and recycling system. First, setting up the "reverse logistics" network can be very challenging. There is a need for better reprocessing technologies, particularly for polymer composites. Specially materials and reinforcing materials in polymer composites often create a nuisance in the recycling process. Standardizing material types would facilitate recycling, but would also inhibit development of new materials which might improve product performance.

The use of recycled materials in the manufacturing process poses a number of problems. Some recycled "raw" materials are more expensive than their virgin counterparts, particularly for some polymers. Quality control is made more difficult when the range of material properties is greater due to contaminants and varying feedstocks.

Furthermore, only a handful of products are currently designed to facilitate recycling. For example, flat-panel displays have been developed and are gaining wide market entry without consideration of their recyclability. Finally, the recycling process can also create its own environmental impact, resulting from transportation, facilities construction, facilities operations and waste generation.

5.2 Design for Environment. The increased emphasis in system's thinking, driven in part by the fact that end-of-life issues are now to be taken into consideration during product design have led to what is often referred to as "Design for Environment" (DFE). Synonymous phrases include "Environmentally Conscious Design" or "Green Design." The interest in DFE is growing worldwide.

5.2.1 DFE in Japan. In Japan, DFE is strongly correlated to a culturally ingrained sense of avoiding waste and conserving limited resources, as observed during visits to Toyota and Toyo-Seikan. Lack of space is a key motivator in Japan. This explains the emphasis on avoiding landfills by means of incineration and take-back initiatives.

In Japan, there is a strong emphasis on the development of DFE tools. Hitachi demonstrated several examples, as did the governmental laboratories. Several tools shown were focusing on Design for Disassembly and Design for Recycling, and NEC is developing its own Life-Cycle Analysis tool. A key reason for in-house development was, interestingly enough, the language barrier: in order to introduce DFE and LCA tools, Japanese companies need a tool written in Japanese rather than English.

Another key problem observed was the lack of integration with other design and management tools and practices. The sense of priority seems still to be with cost and quality at the engineering level, and Hitachi and others indicated that DFE is not completely adopted and prevalent throughout Japanese corporations. The connection with management tools also is lacking (still). It was very interesting to note that NEC had never investigated the economic pay-off of its environmental R&D laboratory in its 29 years of existence, until last year. Instead, management sees environmental efforts as part of "being a good citizen."

5.2.2 DFE in Europe. In Europe, DFE was also prevalent, but several industrial sites visited also emphasized that DFE should not be a stand-alone activity, but integrated throughout the product realization process. Still, there was no "magic" solution for how to integrate it throughout the business. At Volvo, this was cited as being a problem. Along similar lines, DaimlerChrysler stated that having experts at the corporate level *only* did not work; experts need to be at the business unit level, close to the engineers and managers who are directly involved with the product and process design and management issues. It seemed that for most companies a primary motivator was "success stories" where environmental thinking was also beneficial to the bottom-line in some way.

In general, EBM is seen by many in Europe and Japan as a natural extension of lean manufacturing and/or concurrent engi-

neering, whereas in the US, it is still often viewed as a separate activity with no "value-added." The European EBM/DFE support strategies appear to have evolved into a group of experts at the corporate R&D level, with few dedicated DFE/EBM experts at the business unit/manufacturing plant level. Integration with company wide information systems (and beyond to suppliers) is being pursued.

In Europe, two studies were performed which focused on Small and Medium-sized Enterprises (SMEs) that highlighted the importance of economic and environmental win-win situations even more. In a Dutch study, it was stated that SMEs were many times eager to be helped, but that as soon as the consultants left, the motivator seemed to have gone as well. The reasons cited were that SMEs tend to think short-term and do not have many resources to spare. A recent Swedish study confirmed this. An unresolved issue, therefore, is how to create the motivation for self-sustaining efforts after initial analyses have been performed by an external party.

From an education perspective, European universities seemed to be further ahead in integrating DFE into their curricula. Both in Europe and Japan, there are several ongoing research efforts, major national initiatives, and conferences. However, in Japan, DFE is not yet integrated in the curricula, and is mainly driven by elective courses and individual faculty interest.

In DFE and EBM alike, typical questions posed are:

- What is the environmental impact?
- Where does it occur most?
- What should we do about it?
- What is it going to cost us?

Hence, assessment tools are crucial and should ideally be easily validated, easy to use, objective, reproducible and enhance understanding. Throughout, it is generally agreed that one should not focus on one life-cycle aspect solely, but take a system's and life-cycle perspective.

5.3 Life-Cycle Analysis. Life-Cycle Assessment (or Analysis), LCA, is defined in ISO 14040 as "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life." It was observed that LCA is widely used in Europe. In Japan it is less widely used, although there are apparent national efforts to develop LCA tools. A key motivator is the ISO 14000 certification. To support LCA, there are a wide variety of software packages available, e.g., Volvo developed the Environmental Priority System, the Dutch developed the Eco-Indicator (embodied in Simapro software), and in Germany several extensive databases plus software tools (e.g., Gabi) have been developed. However, LCA is mostly done by experts, either internal (e.g., corporate R&D) or (hired) external consultants. Furthermore, the LCA tools are not integrated with other analyses yet. Siemens cited this as being a problem.

A problem with LCA that was mentioned during the TU Delft visit is that there is no general consensus on a "standard" metric for measuring environmental impact, and thus a wide variety of interpretations are possible. In Europe, some companies have been promoting a "universal" single impact measure as provided by the Dutch Eco-Indicator, but this was met with strong opposition because many felt that this would result in using LCA more as a competitive tool than as an tool for true environmental impact improvement. Nevertheless, common criticisms regarding LCA are that it is not tied to business perspectives, too academic, too vague, difficult to perform, etc. Key of course is a lack of data. In The Netherlands, the opinion was voiced that LCA has a problem in that it does not capture "value." Nevertheless, there does not appear to be any viable alternative, and LCA seemed to be well established in all major companies visited. Even more, certain Scandinavian governments now require that an LCA study be performed as part of a bid on a contract.

5.4 Economic and Environmental Win-Win Situations

One of the most promising aspects of the systems approach involves strategies that simultaneously decrease pollution and improve profitability. One example commonly cited is the Xerox Corporation, which was able to realize a \$200 million profit by spending \$10 million to recycle toner cartridges. Another example was observed during the Toyo-Seikan site visit, where the panel observed a new stretch drawing process for forming thin-walled steel cans. A tin free steel is laminated with polyester film, eliminating the need for painting, lubricants, coolant water and subsequent wastewater discharge. The absence of tin facilitates recycling of the steel and the laminated polyester film is reported to discharge no toxic fumes when burned off for recycling. The process is more profitable and consumes less space, steel, water and energy than the conventional method.

In Japan, a longer-range economic perspective is taken than in the U.S., with firms being more patient about investing for expected longer term payoff. An example is the Fuji-Xerox plant visited, which integrated a product take-back and disassembly unit within an assembly facility. The disassembled components are cleaned, inspected and reassembled into new products. While the assembly plant is profitable overall, the disassembly unit is still not cost-effective compared with the option of using all new components. However, they continue improving its efficiency in anticipation of future regulations, expecting to realize a competitive advantage by being first to achieve cost-effective disassembly and reuse.

While anecdotal evidence of "win-win" situations is inspiring, there is a great deal of controversy regarding the impact of environmental controls on the *overall* profitability of the firm [8,9]. Some assert that there is no tradeoff between pollution prevention and "the bottom line" for the firm; that measures taken to prevent pollution also increase efficiency and profits [10].

Others argue that if EBM technologies always simultaneously decreased cost and improved product quality, the marketplace would have already achieved its "lowest polluting" potential without government intervention. They point out that although initial efforts to reduce pollution very often result in some savings for the firm, there often comes a point where increasingly stringent regulations incur unavoidable cost increases. (However, noncompliance might result in an even more significant cost increase.)

Interestingly, few (if any) companies have yet quantified the link between environmental assessments and business/economic assessments. Even companies that take a pro-active stance by going beyond mere compliance present the economic assessment mostly on a case-by-case, anecdotal basis and not systematically. Some promising initial research has determined that firms that adopt a single stringent global environmental standard, regardless of local standards, have higher market values [11]. These types of analyses are in their infancy, and rely heavily on self-reported assessments of general managerial practices. More in-depth analysis of the correlation between specific technologies and their economic impact, is needed.

5.5 Stake-Holder Collaboration.

The most striking distinguishing feature of the European approach is the way in which environmental protection legislation is formulated. Regulators, citizens, academia, industry and consultants interact in a more cooperative, less adversarial manner than in the United States.

In Europe, the Dutch are often cited as having the best cooperation between industry and government, followed by the Scandinavians. In 1989 a shift occurred in the Dutch Ministry of Housing and Spatial Planning (the equivalent of the US Environmental Protection Agency) when it shifted from the classical media (air, water, land) based approach to a industry sector based approach, sometimes referred to as the "polder model." Furthermore, the Ministry of Economic Affairs began to cooperate directly with the Ministry of Housing and Spatial Planning. The result is that, in

governmental policy decisions, the correlation between economic and environmental issues is much better understood and managed.

Some limitations to this approach are details regarding implementation (which can be easily overcome) while others may be more intractable. Within industry, environmental issues and life-cycle thinking have caused a need for more extensive data reporting and tracking between Original Equipment Manufacturers (OEMs) and suppliers. All large Original Equipment Manufacturers like DaimlerChrysler, Ford, Toyota, etc. have programs to track use of hazardous or substances of concern. This data is often also used by OEMs for monitoring supplier performance, which creates tensions with suppliers who feel that the data can also be abused for competitive purposes. According to Lucent Technologies, building a trusting and long-term relationship with suppliers is crucial and cooperation with other partners in the supply chain is critical. Furthermore, a comprehensive strategy must be pursued, such as developing a set of recommended alternatives rather than simply "black-listing" certain materials. For example, environmental guidelines can be used for purchased components, supplier-sited manufacturing processes, and manufacturing equipment. In general, these guidelines fall short of clear mandates but represent commonly accepted best practices across a supply chain or industry sector and initiate a flow of information from Original Equipment Manufacturer to its suppliers. Cooperating with suppliers and investing in development of new materials and processes through knowledge exchange can facilitate more dramatic changes. However, though some companies such as Ford have supplier classes in ISO 14000, the amount of technical collaboration between OEMs and suppliers to stimulate environmental innovation and management is (still) low in comparison to other efforts such as quality management.

Two more serious limitations to employing the highly collaborative Dutch approach in the United States are the traditionally adversarial relationship between government regulators and industry, and the litigious nature of the US society. While managing a cooperative interaction in a small country with a rather homogeneous population is admittedly much easier than doing so in a country as large and diverse as the United States, there is much to be gained from improving collaborations between US stakeholders.

5.6 Symbiotic Thinking and Industrial Ecology. Several companies clearly have evolved beyond "business as usual" and can be viewed as "thinking outside the box." At Interface Flooring Systems, the approach is centered on "quantification, qualification, symbiosis." This means that once a waste stream's amounts have been defined (quantification) and their severity assessed (qualification), an attempt is made not just to reduce it, but to find an outlet that can actually use the waste as a feedstock. These outlets can be other industries, and a symbiotic industrial ecosystem (as promoted by industrial ecology) can be obtained.

However, this symbiotic approach can also take place more directly with nature. Interface Flooring is using natural materials for some of its carpet products, e.g., animal hair and recently corn based fibers. Similarly, DaimlerChrysler is using natural reinforcing fibers (flax or sisal, depending on location) instead of glass fibers in some of its polymer composite components because these natural fibers can be more easily decomposed, both when recycling production scrap and also at the end of the useful life of the vehicle. One of the most intriguing aspects of this project was an attempt to look at this from a life-cycle viewpoint, including working up the supply chain with the flax growers in order to ensure a uniform material.

This paradigm shift of viewing groups of industries and even nature as a large interconnected system does pose some problems. Both Interface and DaimlerChrysler noted that an entirely new supply chain had to be set-up. For example, DaimlerChrysler had to ensure a consistent crop quality, which even meant redesigning farming equipment, and developing quality control systems to deal with unavoidable variations in the natural fiber "manufactur-

ing" process, such as the amount of rainfall. Another example is efforts by Archer Daniels Midland in identifying a use for waste flyash (similar to cement) generated by their fluidized bed coal combustion system. The fluidized bed system successfully decreases air pollution, but the chemical composition of the waste flyash depends in turn on the composition of the coal, which varies greatly. As a result, the flyash is unsuitable for many applications. In essence, the same manufacturing process quality control systems that have only recently been embraced by individual manufacturers will need to be embraced on a much larger scale.

5.7 From Selling Products to Selling Use. The technical and economic difficulties with recycling described above can be avoided though product reuse and component remanufacturing (at least temporarily). Component reuse is well established in a number of sectors (e.g., automotive components, manufacturing equipment) and is pursued primarily when it makes good business sense. Most remanufacturing is performed by third-party remanufacturers, with a few exceptions. Caterpillar, Xerox, Kodak and Dell actively pursue remanufacturing and reuse as part of their business strategy.

Caterpillar's "Reman" offers remanufactured engines and engine components at prices below that of comparable new components. Engine blocks are first disassembled, flushed and inspected, then resurfaced. Crankshafts are reground, polished and checked. Bearings, seals, gaskets, etc. are replaced with new components.

Dell's "remanufactured" computers are those that have been returned by the consumer within the 30-day total guarantee period. These computers are disassembled, rebuilt to original specifications and then tested. Dell's remanufactured systems cost \$100-\$600 less than comparable new models, and come with the same warranty. However, they do not allow for modification of predetermined system configurations. Dell does not currently offer a standard leasing option, but they do offer to dispose of end-of-use systems for business consumers.

In Europe, such reuse and remanufacturing have long been part of the replacement parts business, for example, DaimlerChrysler's engine remanufacturing facility. The next logical step would be to improve the cost-effectiveness of disassembly and remanufacturing technologies.

In addition, there is growing interest in a paradigm shift from selling a product to selling a service. In such an arrangement, the customer essentially leases the product for a predetermined time period, or perhaps pays a monthly fee for the defined service. The Dutch government has issued several studies to determine how a shift toward selling services would promote sustainable development. Japanese electronics companies use the phrase "inverse manufacturing" to refer to this concept, and are exploring concepts involving modular consumer electronics systems, where one module (such as a monitor) might serve the function currently fulfilled by two or more consumer products (such as a television and personal computer).

Such leasing arrangements have been in place for automobiles and copying machines for some time. For the manufacturer, advantages of this approach include far greater control over the condition and timing of the products' return to the manufacturer. For example, the Fuji-Xerox system includes a system for keeping maintenance, repair and reliability records for each product, which is considered at the time of disassembly.

Regarding remanufacturing, there is an untapped potential for "design for component reuse." The panel observed no examples of product components being designed specifically for easy disassembly so that certain components that can be cost-effectively cleaned, remanufactured and re-assembled into "new" products.

However, it is not yet clear how customers will respond to this new approach. So far, leasing arrangements have been successful for high-cost, high maintenance products such as photocopying machines. It remains to be seen whether customers will be satisfied merely renting other types of products where "pride of ownership" is an important attribute.

6 Industry Specific Issues

6.1 Regional Trends in Electronic Industry. Both Japanese and US companies are highly responsive to activities in Europe, particularly the WEEE directive, with the primary focus being elimination of halogenated flame retardants (typically BFRs) and lead-containing solder. ISO 14000 certification is a key concern for Japanese companies; in Europe there is a moderate effort to complete certification; and in the US, it is primarily the international companies that are actively pursuing ISO 14000 activities. While the US leads in developing alternative PWB technologies (such as microvias), the Japanese are most aggressively pursuing these alternatives in commercial products. The motivation is typically reduced size and increased performance for portable consumer products; however, the processes used to manufacture these boards typically use less water, energy, and material resources. Hitachi, Sony, NEC, and many other companies (IBM, Motorola, etc.) are all using this approach in some of their products.

Europe has several countries with take-back legislation in place, but The Netherlands appears to be the only country to date with a well-developed infrastructure for collecting and recycling computers. It is expected that other members of the European Union will follow suit within the next few years. The industry representatives that were visited indicated that there is a strong push to be able to document EBM practices in both their own manufacturing processes as well as from suppliers. Both Philips and Lucent are especially active in this area. Companies such as Siemens offer "green" products in parallel with conventional, but with a price differential.

US electronics companies are responding to activities in Europe by investigating alternatives to lead solder and BFRs. However, these activities are moving more slowly and with more reluctance than in Japan. The general feeling is that the benefits to the materials far outweigh the environmental risks. There is more interest in disassembly technologies and design for disassembly. There is also a strong emphasis on metrics and supply chain management. Most recycling activities in the US are occurring (or have occurred) as partnerships with OEMs. Examples of this are Micro Metallics (Noranda and Hewlett-Packard), Dell Computer and Resource Concepts Inc. in Dallas, AT&T/Lucent and Butler-MacDonald in Indianapolis, and IBM's Aurora project in central NY state.

6.2 Regional Trends in Automotive Industry. One of the disturbing trends that surfaced during the course of the site visits conducted during this study concerned a significant difference between the U.S. companies and those in Europe and Japan. Individuals from U.S.-based plants frequently commented that existing regulations tend to inhibit technology changes that could result in positive environmental effects. It seems that once a given process technology has been formally approved, as new (better) technologies are developed the burden to pursue the formal approval of these new technologies is often so large that the technology changes are not pursued. This appears to be in sharp contrast to industry-government interactions abroad where there is a common vision regarding technological innovations directed at environmental improvement and economic development.

All of the automakers and suppliers that were visited, as well as those identified via literature surveys, are pursuing or have achieved some level of ISO 14000 certification. While the European-based organizations appear to view this pursuit as completely consonant with their overall environmental strategy, attitudes in Japan and the U.S. seem to be more focused on certification as a hurdle to achieve market entry. Automakers in the U.S., Japan, and Europe all have well documented environmental strategies. In the U.S. the Tier 1 suppliers are also literate with regard to environmental issues, although there was some variability evident in the commitment level of the suppliers to environmental issues. All automakers are asking their suppliers to become

ISO 14000 certified, and again, there was variability in where the suppliers stand in this certification process. The expectation is that this ISO certification requirement will be passed through the supply chain.

The management and synthesis of information across the automotive supply chain is an issue that extends well beyond the topic of environmentally benign manufacturing. There are a number of open issues about how to propagate environmental measures across the supply chain. For example, as the automakers track their energy usage from year-to-year, how can the energy usage of the suppliers be properly incorporated? Supplier data on emissions, wastes, and resource consumption is also needed, and techniques for combining all this information are needed. It is clear that much work will be required before some of the ISO 14000 standards will be met (e.g., ISO 14020 series on eco-labelling).

Several of the automakers were queried about corporate trends in selling "product use" rather than the product itself. Under such a scenario, the manufacturer (or their agent) would retain ownership of the product and consumers would pay to use the product. While they were aware of this concept, there does not appear to be any concerted effort to move the industry in that direction. On the other hand, the auto industry does distribute approximately 30% of its vehicles through lease programs, and one could argue that this is in fact "selling use." There did not appear to be any significant differences in attitudes to this idea across the sites that were visited. Caterpillar, which is also in the transportation business, on the other hand, is moving very aggressively to selling product use.

The notion of product stewardship, extended producer responsibility, and vehicle take-back represent considerable challenges to the auto industry. This is especially true in light of the trend in the U.S. for automakers to delegate more and more of their manufacturing tasks to their suppliers. It is unclear what the suppliers' responsibility will be for end-of-life vehicles. Certainly, communication with suppliers indicated that most do not believe they have any extended responsibility for a product after it has been sold to their customer. It is likely that these issues will first be addressed and resolved in Europe.

One of the principal differences that was evident between the U.S. and Japan/Europe was the attitude of consumers toward vehicles. While consumers in the U.S. have recently complained about the high cost of gasoline, the prices are still well below the prices abroad. The high cost of driving and maintaining a vehicle in Europe/Japan has, in part, created consumer habits/attitudes that differ remarkably from those practiced by individuals in the U.S. It is hard to imagine wide consumer acceptance in Japan/Europe of Sport Utility Vehicles that are presently so popular in the U.S. Furthermore, a large gap exists between the environmental awareness of consumers in the U.S. and those in Europe and Japan, and efforts should be undertaken to better educate the U.S. public on matters related to the environment and resource conservation.

7 Material Issues

7.1 Metals. Metal manufacturing has always been intensely interested in recycling and reduction in the use of energy and materials. As material requirements become more stringent, and pressures increase to minimize energy usage and greenhouse gases, the metal manufacturing industry continues to look for improved manufacturing methods. Today there is an emphasis on the use of new, lighter weight materials instead of traditional ferrous materials. There are implications for the scrap/recycle stream that need to be considered, as well as implications in material development. These implications include alloy and part processing, logistics of scrap collection, sorting and shipment, and methods of recovering advanced materials either in their original form, or in separating the individual metal values from the material.

Concern was expressed by a number of companies that highly engineered tailored materials (such as graded powder metallurgy

tool steels where the composition varies over small areas) cannot be recycled without losing their structure. Other recent areas of materials technology emphasis, such as nano-materials, present similar problems: because the alloying elements are so finely dispersed in the alloy, it is not currently possible to recover these alloying elements during recycling.

In view of the importance of achieving light weight in all applications that use energy during their life cycle (such as cars and trucks), iron and steel face a challenge. Although iron and steel are stronger and stiffer than aluminum and magnesium, they are not attractive if they result in a weight and energy usage penalty to the final product. Thus there are a number of research projects aimed at making them lighter.

In the United States, a consortium of iron foundries and their suppliers is sponsoring research on the production of "thin-wall" iron, that is, iron castings having wall thicknesses down to 2.5 mm. Research is needed because if the proper melting and pouring procedures are not followed, cast irons solidify with a hard, brittle structure in thin sections, which is not useful in engineering applications. The research also focuses on the molding technology required to control wall thickness.

Research into very high strength steels is going on in a number of organizations world-wide. In Japan, researchers at the National Research Institute for Metals are developing high strength steels, supported by Japanese steel companies. One project is investigating thermo-mechanical treatment of low-alloy steels to obtain micron-sized grains to yield steels with strengths in the 800 MPa range. Similar studies are under way in European and US laboratories. Among the problems posed are those of joining the material without altering its microstructure. Some possible solutions include the use of extremely narrow gap arc-welding techniques, one-pass laser welding, and low temperature joining techniques.

7.2 Metal Processing Issues. In terms of priorities, it was pointed out by a number of companies that the three largest contributors to pollution in metal manufacturing are machining (the use of lubricants), casting (air pollution from binders) and surface conditioning (cleaning, painting and plating).

Dry (or almost dry) machining is a major research emphasis in Japan and in Europe. In the United States, we were told by all three automobile manufacturers that developing dry machining is an environmental priority for their companies.

Another approach is to eliminate machining wherever possible. For instance, at Volvo, holes in the truck chassis are punched instead of drilled. This is done to facilitate recovery of the metal removed, as punchings are easier to re-melt than turnings. The punchings are sold to their supplier foundry.

7.2.1 Casting. At Daimler, casting was described as the manufacturing process of the future, because components could be combined in castings, thus eliminating machining and assembly operations. For casting to reach its full potential, however, dimensional control and reproducibility must be substantially improved. The foundry industry in the United States has realized this, and is sponsoring a number of benchmarking studies to determine current casting dimensional capabilities.

Sand foundries comprise about half of the metal casting establishments in the United States. These foundries make the molds into which the molten metal is poured from sand, held together with a mixture of clay and water. In ferrous foundries finely divided bituminous coal is added to the mixture to improve the surface finish of the casting. Cores, which make the hollow parts of castings, are made of sand bound with thermosetting resins. When molten metal is poured into the mold, the thermal decomposition products from the coal and resins are released into the atmosphere. These decomposition products include greenhouse gases and other gases that are listed in the EPA's list of hazardous air pollutants. The foundry industry is actively pursuing binders and mold additives to reduce effluents from the mold. One promising approach is the addition of oxidizing agents to the mold to

more completely combust the decomposition products. Current research shows that the addition of these products not only cleans the air, but also reduces the amount of clay needed to bond the sand.

The Department of Defense and the metalcasting industry have built a modern sand foundry to study low emission products and processes in greensand foundries. The \$50 million facility, called the Casting Emissions Reduction Program (CERP) facility, at the closed McClellan Air Force Base in Sacramento, CA, permits the measurement of air quality at various stages in the production process. The projects include both environmental and dimensional studies that would otherwise disrupt production in a commercial foundry. This is a unique facility that is not found in other countries.

Non-ferrous casting methods have recently been expanded to include semi-solid casting methods, in which an alloy is heated to a temperature between its liquidus and eutectic temperatures and then injected into a steel die. Both aluminum and magnesium alloys are made this way. Dimensional control is excellent, and castings often need no machining to be used.

There have also been substantial improvements in the quality of pressure die castings in recent years. This net shape process is now capable of producing dimensionally accurate parts with high property reliability. The success of semi-solid casting methods for non-ferrous alloys suggests that more efforts should be made to extend this method to ferrous metals and alloys. The initial attempts to develop ferrous die casting twenty-five years ago were commercially unsuccessful; it may be time to re-visit this technology.

7.2.2 Metal Coating. Surface protection of metal, which includes coating and plating, is a major contributor to environmental problems. Plating operations were an early target of state and federal environmental enforcement agencies. To a large extent, the plating industry is no longer considered to be a major polluter, but painting is now seen as a major environmental problem.

The primary problem in painting has been the use of organic solvents as the vehicle for the pigments. These solvents require extensive treatment of the exhaust air from the painting operations before the air can be released to the atmosphere. Although there are methods that clean the solvents from the air, they require extensive use of fans, filters and other treatment equipment. The systems are expensive to build, and expensive to operate. (One European OEM installed such a system, only to discover that changing the coating method from solvent to water base would have accomplished the same goal at a fraction of the cost.) Water base systems have been developed, but they also present problems, both in the product quality and in treatment of effluent.

One technology that has been "almost" developed is the coating of steel sheet in the steel mill. The coatings are sufficiently pliable that the sheet can be stamped using conventional stamping dies. But stamping companies are reluctant to use the process. They are concerned about scratches on the surface as a result of handling problems during stamping, edge cracking of the coating during trimming, and color match from coating batch to batch. Nevertheless, the application of the clear coat in automobile and appliance factories could be done using this technology, if methods were developed to eliminate these concerns.

7.3 Implications of Take-back Laws on Metal Alloys. The implications of take-back laws bear consideration. In the case of automobiles, the average car lasts for 12-13 years in the United States, and has traveled about 110,000 miles when it is scrapped. From the standpoint of the metals industry, this means that scrap that met the specifications of the industry thirteen years previously must be accommodated in the recycling procedure. Another implication of the changing material composition of the automobile is that conventional scrap markets, based primarily on ferrous materials, will be faced with dislocations over the next two decades. There are implications for the entire infrastructure of scrap

Table 5 Some potential environmental problems with polymers

Phase	Problem
Petroleum extraction, refining,	Leaks, spills, releases, solvents, energy, HAPs, VOCs, waste and wastewater, use of non-renewable, limited resource.
Primary conversion	Toxic materials, energy usage, HAPs, VOCs wastes and wastewater
Processing	VOCs, HAPs, energy, hazardous materials, wastes and wastewater
Use	Out gassing, unreacted monomer, release of residual solvents, plasticizer etc., degradation and failure of the product, energy usage, interaction with environmental liquids, acids, foods etc.
End of Life	Solid hazard, litter, leaching, hazardous release during incineration, land fill shortage, unsustainable

collection, sorting and distribution, if metal recycling becomes the responsibility of the original equipment manufacturer, instead of the scrapyard.

This may imply that alloy compositions would have to be frozen, as development of a new alloy for an engine block may leave the manufacturer with large quantities of the old engine block material—and no market for it—at some point in the future. Modern alloys are made to more stringent specifications than those used previously, even when the alloy designation does not change. Also, as noted above most alloys can only be recycled a few times before they have dissolved unacceptable levels of impurities. (Each time an alloy is melted it dissolves minute quantities of the crucible or mold material; eventually these add up and the alloy no longer conforms to specification.) Thus the possibility of take-back laws appears to complicate the picture for metals and alloys. This is even more true with polymers, as discussed next.

7.4 Polymers. The US polymer production continues to grow and is now on the same order as metals. However, over the last ten years the plastics segment has been growing at three times the rate of the metals [12]. This success is due to the low cost, lightweight and excellent properties of polymers for such applications as food containers, packaging materials, textiles, films and engineered parts. In spite of their ever expanding use however, polymers retain an image of being environmentally unfriendly. The potential environmental impacts associated with the different life cycle phases of polymer products are listed in Table 5.

In Table 5, several reoccurring themes are noted. At various stages in their life, polymers exist as low molecular weight hydrocarbons, and various hydrocarbon solvents are often employed in their processing. Consequently, there is always a threat for leaks or spills to occur, or for the escape of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). Furthermore, in the case of some polymers, the precursor chemicals, the intermediates, or the catalysts can be quite hazardous. In fact the chemical industry, which produces the polymers, has historically been one of the leading toxic waste sources in the United States [13].

A second important theme for polymers is energy usage. Polymer processing uses significant amounts of energy. For example, if the entire plastics industry experienced only a 1% improvement in process efficiency, enough energy would be saved to power over one million homes a year [14].

The chemical industry spends billions of dollars annually on pollution prevention and control, and has hundreds of billions of dollars invested in pollution control equipment. These measures have resulted in significant reduction in pollution and waste over the past decade. However, the utility of continuing down this “end of pipe” treatment approach may now be reaching a point of di-

minishing returns. It appears that new approaches are necessary to address the staggering problem posed by the chemical industry. Recent studies have outlined new strategies based on “clean technologies” to improve the chemical industry [15]. The basic clean technologies strategies to reduce wastes and usage of materials of concern include: 1) waste recovery and materials exchanges, 2) waste reduction, including equipment redesign for more efficient processing, and 3) materials substitution.

7.5 The Polymer Take-Back Challenge. While there are a number of potential environmental consequences to using polymers, there is one reoccurring theme that presents a major challenge to the future development of polymers, composites and advanced materials of all types. This is the potential conflict between performance and the ability to either incorporate recycled content into the material and/or recycle the engineered material for use in high value applications at the end of the original product’s life. Often, the very same feature that appears to be responsible for good performance, the use of multiple materials in a symbiotic way, may present an enormous challenge in both of these areas. First, engineered materials are typically complicated and use precise mixtures making them intolerant to the variation that often comes with using recycled content. And secondly, because of their heterogeneous nature, these complex materials are either an enormous challenge to separate, or if not separated, they become a source of variation for most waste streams to which they could contribute in their end of life. Hence the significant benefits to using engineered polymers and polymer composites in the use phase are often counter balanced by a significant end of life dilemma. The new (dual) European directives for increased fuel economy and product take back for automobiles are forcing this issue to be considered in depth by those who wish to compete in the European automobile market.

During our various site visits we found what appeared to be clear regional preferences for certain end-of-life approaches. Many of the European countries have, or are in the process of developing, extremely comprehensive collection schemes for recycling. However, the end of life treatment for plastics appears to be incineration after it has been separated from the more desirable metals and glass (e.g., at MIREC). The panel also found that currently, Japan also incinerates most of its plastics. In the US most plastic waste is landfilled. However, in areas of very high population densities, e.g., some east coast states, plastics incineration is now increasing.

In general, however, the panel did see some evidence of a move away from incineration and toward recycling in both Japan, due to the new recycling laws that are scheduled to take effect in April 2000, and in the European Union where recycling laws will limit

the amount of incineration. Furthermore, in the U.S. many large urban areas already have well-developed collection programs intended for recycling. Yet the financial success of plastics recycling schemes to date has been very limited. The problem in most cases is related to infrastructure development and the reverse logistics process. In simple terms it is very hard to get an adequate waste stream in terms of volume and purity that can supply the needed material for a viable product. At the heart of this issue are some of the very attributes that make polymers so successful in the first place; low weight and low cost. Low weight actually increases reverse logistics transportation costs per unit of plastics. And low cost means that transportation, cleaning and sorting must be very efficient in order to keep the costs below those for the virgin material.

The chance for successful plastics recycling increases as the waste stream quality and quantity increase and as the cost of the virgin material increases. Success stories to date are PET soda bottles and Nylon carpet materials. Both are available in fairly large quantities that can be separated efficiently. Furthermore, both can be recycled back to their original monomer components in a recycling scheme akin to metal recycling back to basic metals. There is also significant interest in the development of recycling schemes for high-end engineering thermoplastics, which are typically used in automobiles and electronic equipment. These include ABS, HIPS, and PC. The EPA and DOE are currently funding a Stakeholder Dialogue process at Tufts University to examine the barriers to this technology. And there have also been several pilot studies to look at infrastructure issues including ones in San Jose, CA, Somerville, MA, and Binghamton, NY.

New technology could turn around the plastics recycling problem, but the technology would have to address the fundamental systems issues. For example, one approach is to use shredding to densify the plastic for efficient transportation, and then technology to sort it. To facilitate this, MBA Polymers has developed new proprietary technology for efficient sorting of mixed shredded plastics at high rates. MBA claims to be able to sort shredded plastics at the rate of 4 tons/hr. Other sorting technologies are based upon infrared reflection (but this cannot handle black plastics) and Raman laser spectroscopy, which can deal with black plastic and even identify some fillers and additives. Small scaleable recycling units that are operated locally, presumably near a suitable waste stream, could also be used to reduce the transportation cost. However, various depolymerization technologies, such as those used with PET and Nylon generally require large investments and hence much larger processing volumes, making them hard to scale down.

In some cases recycling infrastructures are set up to capture particular target materials because they are either valuable or troublesome. For example, among thermoplastics, PVC usually requires special handling because it can produce HCl during incineration, and it is a contaminant for some other plastics during recycling. While in Japan, the panel learned of a sophisticated infrastructure to collect and recycle PVC back into pipe, and in another application into window frames. The significant features of the Japanese infrastructure were;

1. careful collection, and sorting of construction waste by a licensed technician on site (this is paid for by the site owner),
2. reprocessing of the PVC to established standards,
3. financial support in terms of a subsidy provided by the government to allow the recycled material to compete with the virgin material, and
4. careful development of the application. For example in the case of the PVC window frame, processing involved the development of a sophisticated 3 material co-extrusion process which could produce a frame cross section with a PMMA exterior, virgin PVC interior and recycled PVC core.

Furthermore, there is an excellent market for this window frame in the north of Japan where current frames are predominately aluminum.

Such infrastructure developments could payoff by cleaning up feed streams for other plastics and by preventing pollution from improper disposal of PVC. Furthermore, as volumes and efficiencies increase these kinds of model efforts could become sustainable. Similar recycling schemes have been supported in Europe to make 3-layer PVC pipe. An equivalent PVC pipe enterprise in the U.S. does not exist due to shortcomings in our infrastructure [16].

Work is also being done on the recycling of thermosets too. While at NIRE in Japan, the panel saw a project on the recovery of phenol from both phenolic and epoxy resins by liquid phase decomposition. It allows recovery of phenols at an efficiency of about 60 to 80% by weight directly from factory waste. This compares very favorably with current recovery scenarios based on pyrolysis and super critical water, which can only give efficiencies of about 20% due to the recombination of radicals. Interest in this work has lead to a joint research project with Sumitomo Bakelite, Hitachi Chemical and JVC to start in the near future.

Clearly the easiest products to recycle would be those made of a single material, or simply separated from other materials that require no secondary operations like, paint, label or surface coating removal and cleaning. Crucial in this area is design for recycling. Manufacturers are moving in this direction by redesigning products to facilitate take back. For example, both Ford and Toyota have designed new bumper systems from a single polymer. Also, new floor covering systems (e.g., as produced by Interface Flooring) are now designed such that the variety and amount of materials are reduced, and the interfaces between layers are "zipable" to easy disassembly during recycle.

Plastics can also be used in various by-product synergy schemes. In Japan the panel learned of projects to use plastics as a reducing agent in blast furnace steel production. In several pilot demonstrations, plastics have been used as a carbon source in steel production to reduce the oxygen content. Furthermore, because of the higher hydrogen content of plastics compared to the typical reducing agent, coke, the Japanese have argued that some hydrogen reducing will take place, thereby reducing the carbon emissions during steel making. Some Japanese firms are using this scheme to help meet their Kyoto Protocol targets. On the other hand, a European steel making plant dismissed this argument as marginal. Regardless, the use of plastics as a reducing agent provides an intriguing end of life scenario for plastics and is being actively pursued in Japan, and Germany.

Clearly, polymer and end of life treatments provide a rich opportunity for new technology and infrastructure development. Currently USCAR in cooperation with the APC is developing a plastics-in-automobiles roadmap due out in the Spring of 2000 which should provide additional guidance in this area.

7.6 Bio-Materials. Many of the proposed solutions to a wide range of environmental issue for polymers involve the development of new materials. Certainly, one of the most intriguing areas of new materials development is in the area of biomaterials. In many cases the goal is to grow the feedstock for a new class of biodegradable polymers. For example, currently there are several commercial initiatives to develop biodegradable polymers from corn. Two possible routes to do this include the processing of corn sugar to polylactide (PLA) and several routes to produce polyhydroxyalkanoate (PHA). In general, these products look promising but raise a host of life cycle issues that require closer scrutiny. These include; 1) potential land use conflicts, 2) net energy consumption, and 3) net greenhouse gas production. For example, in a recent analysis it was found that the routes to PHA from corn generally require more energy than the conventional routes for equivalent polymers from petroleum [17]. On the other hand, PLA production appears to be energy competitive, but will lead to significant amounts of greenhouse gases. In any case one common element for all of these new materials scenarios is the need for

major new infrastructure. For example, when referring to the production of PHA, Grengross and Slater [17] state, "This processing infrastructure rivaled existing petrochemical plastic factories in magnitude and exceeded the size of the original corn mill."

A related area is the growth of various fibrous plants such as sisal and flax to be used as reinforcements in polymer composites. DaimlerChrysler makes automotive panels using these materials. Johnson Controls, Inc uses ECO-COR, a door material that includes renewable natural fiber and polypropylene blend. For their fiber reinforced panels, DaimlerChrysler, with the support of the German government, developed the infrastructure to produce fibers of uniform properties in spite of variations in growing seasons. In this application, natural fibers replace glass fibers which present particular challenging end of life problems. Natural fiber composites, are easily incinerated for energy recovery, an option that is not currently available for glass fiber composites. Alternatively, they could be used with a biodegradable polymer matrix to make a biodegradable composite.

Synthesis with biodegradable linkages has also proven successful. For example, the Fraunhofer IGB in Stuttgart is looking into the synthesis of "natural" polymers by the inclusion of amine and ester bonds to promote biodegradability. Along this line they have produced an alternative for cellulose called Ecoflex that shows good properties, but requires additional work to show economic feasibility and to develop processing techniques.

Many of these new bio-materials are intended to be used in packaging applications—a significant source of polymer waste. For example, responding to the environmental concerns of their customers, DuPont has developed new kinds of environmentally friendly containers that can be processed in the identical manner as the contents of the container. For example if the product is a compounding agent, after the entire contents are used, the remaining container can be crumpled up and put into the machine to be processed in an identical manner as the compounding agent. Or, for the case of agricultural products, the potentially hazardous box liner would be water soluble, just as the product and could be deposited into the product applicator and sprayed onto the plants just as the product was. This new kind of product container is called "Rotim" which stands for "return or throw in machine." Although not biodegradable, these materials are "process" degradable and may represent a new, very efficient recycling paradigm for some types of products.

8 Summarizing the Key Findings

To give a high level overview of the EBM activities and relative efforts by region, the following matrices (see Tables 6, 7, 8, and 9) were developed by consensus within the panel after completion of the site visits. They are subjective, but based on observations made during the year-long investigation, and it is believed that they represent the relative trends within the three different regions in the areas of government, industry, research and development, and education. The number of bullets in each cell is intended to be indicative of level of effort and emphasis as much as actual level of success.

Again, it is clear that cultural, geographic, and business needs all strongly influence practices in environmentally benign manu-

Table 6 Government activities

Activity	Japan	US	Europe
Take-back legislation	◆◆	—	◆◆◆◆
Landfill bans	◆◆	◆	◆◆◆◆
Material bans	◆	◆	◆◆◆◆
LCA tool and database development	◆◆◆	◆◆	◆◆◆◆
Recycling infrastructure	◆◆	◆	◆◆◆◆
Economic incentives	◆◆	◆	◆◆◆◆
Regulate by medium	◆	◆◆	◆
Cooperative /joint efforts with industry	◆◆	◆	◆◆◆◆
Financial and legal liability	◆	◆◆◆◆	◆

Table 7 Industrial activities

Activity	Japan	US	Europe
ISO 14000 Certification	◆◆◆◆	◆	◆◆◆◆
Water conservation	◆◆	◆◆◆	◆◆
Energy conservation/CO2 emissions	◆◆◆◆	◆◆	◆◆
Decreased releases to air and water	◆	◆◆◆	◆◆
Decreased solid waste / post-industrial recycling	◆◆◆◆	◆◆	◆◆◆
Post-consumer recycling	◆◆	◆	◆◆◆◆
Material and energy inventories	◆◆◆	◆	◆◆◆
Alternative material development	◆◆	◆	◆◆◆
Supply chain involvement	◆◆	◆	◆◆◆
EBM as a business strategy	◆◆◆◆	◆◆	◆◆◆◆
Life-cycle activities	◆◆	◆◆	◆◆

facturing in the US, Europe, and Japan. In the area of government, environmental regulations are relatively new to both Europe and Japan and there are historical precedents for cooperative efforts between government and industry (in many areas, not just in the environment). Consequently, both of these regions tend to have a more proactive approach to problem solving than does the US. This approach lends itself well to long-term system-level efforts such as development of lifecycle inventory tools and data. Take-back legislation and recycling laws in Europe and Japan are made possible by small, densely populated areas and a limited number of local governments within whom consensus needs to be reached. These laws are also driven by the limited amount of area available for landfills. The US has a long history of environmental regulations that are focused on pollution of specific media (air, soil, and water). This, combined with a tendency towards litigation, is much more likely to produce "point" rather than systems solutions. The governments of Japan and the Europe are involved in infrastructure development and extended producer responsibility, which are almost completely absent at the Federal level in the US.

Corporations in the US are very material and process-oriented and tend to place emphasis on decreased resource consumption (especially water) and pollution prevention. While some of the larger, international firms have started to incorporate environmental issues into business strategies, it is not nearly at the level seen in Japan and the Europe. Included in these strategies is a high priority placed on ISO 14000 certification. In the US, life cycle analyses are becoming more prevalent but they are done in a much more limited capacity than are done in Europe and might more properly be described as mass-energy balance activities. Japanese industry, in cooperation with the government, is very concerned with energy conservation (reduced CO₂ emissions) and

Table 8 Research and development activities

Activity	Japan	US	Europe
Relevant Basic Research (> 5 years out)			
Polymers	◆◆	◆◆◆	◆◆
Electronics	◆◆	◆◆◆	◆
Metals	◆◆◆	◆	◆◆
Automotive/Transportation Systems	◆◆	◆	◆◆◆◆
Applied R&D (≤ 5 years out)			
Polymers	◆	◆◆◆	◆◆
Electronics	◆◆◆	◆◆	◆◆
Metals	◆◆◆	◆	◆◆
Automotive/Transportation Systems	◆◆◆	◆	◆◆◆◆

Table 9 Educational activities

Activity	Japan	US	Europe
Courses	◆◆	◆◆	◆◆◆
Programs	◆	◆	◆◆◆
Focused degree program	—	—	◆
Industry sponsorship	◆	◆◆	◆◆◆
Government sponsorship	◆	◆	◆◆

decreased solid waste and this is reflected in the type of life cycle analyses that are performed there. However, there are clear economic as well as environmental drivers including high energy costs and limited opportunities to landfill waste. European corporations are interested in alternative material development, especially as these activities relate to system level issues including life cycle assessment (LCA), particularly in the area of supply chain management, and design for the environment (DFE), typically for end-of-life issues. Post-consumer recycling has a high priority in light of take-back regulations and decreased landfill space.

Research in the US is heavily dependent upon industry objectives (especially introduction of new technologies) and is therefore focused on materials and processes. Japan's efforts are more closely aligned with applications, implementation, and manufacturing systems. European research is heavily weighted in the areas of implementation, and systems engineering, particularly in the areas of DFE and LCA.

Higher education has begun to address EBM in the European countries to a much greater degree than either the US or Japan. The panel did not identify any degree programs in the US. There are a few formal programs within conventional engineering programs and courses at the graduate level are becoming more common.

Overall it appears that environmentally benign manufacturing in the US is somewhat behind that of the Europe and Japan. However, because activities are more privatized within industry and in many cases are viewed as competitive (both technically and from a marketing perspective) the level of effort may be less obvious. The role of the US government is more reactive rather than proactive and as such there is less willingness to publicize its activities, and more reluctance on the part of industry to collaborate on big-picture issues. It should be remembered, however, the US is a nation of crusaders. It does best when it has "an enemy." There are numerous instances where, largely through technical innovation and collaborative efforts, the US has come from behind. Examples are the automobile industry in the early 1980's and the electronics industry in the early 1990's. In both cases there was a significant amount of industry and government collaboration. It will simply take the US government and industry, in cooperation with educational systems, to determine that environmentally benign manufacturing is critical to our global economic status and extended quality of life.

9 In Closing

This paper focused on issues that face firms in developing environmentally benign manufacturing (EBM). Each region that we visited, the US, Europe, and Japan, has different approaches to developing an environmentally benign manufacturing strategy. Each region has different drivers. In the US, the drivers are the correlation between the cost-savings and the environmental benefit. In Europe, the high population density, a recycle mindset, and the take-back provisions drive environmental policy. In Japan, the drivers are the export economy, high population density and ISO 14000. For American firms with a majority of sales abroad, responding to the US drivers alone is not sufficient. A broader vision that includes environmental considerations as an integral part of the entire system of doing business and engineering is necessary. As mentioned, one of our key findings was that the Japanese and Europeans viewed EBM as a systems problem, and have put in place various aspects of a systems solutions. There was no evidence that the EBM problem is solvable by a "silver bullet" technology. Interestingly, this conclusion is not too different from what was found years ago when the Japanese economy was surging based in part on their new production systems. When the outside world went to investigate the "Toyota Productions System" it was found that their success was not based on technology *per se* but rather a systems based solution, which integrated technology.

It is important to note that this paper presents only some of the information contained in the full study report [3] and we encourage interested parties to read the full report that also includes all site visit reports. We believe that the study met its intended goal, namely, providing an evaluation and classification of issues involved in EBM. In many cases, the study re-emphasized known facts and issues. However, in our opinion, it brings together in one document a large collection of information and case material from all over the world. Clearly, the study identified that the next level of major breakthroughs in EBM will not come from technology alone, but rather from collaboration between industry, academia, and government in engineering, science, and policy. The National Science Foundation is realizing this as well and as a direct result from this study, it already has reworded and refocused some requests for proposals in this area. More internal and external collaborative efforts of the National Science Foundation and other funding agencies (like EPA and DOE) can be expected.

Acknowledgments

We gratefully acknowledge Dr. Delcie Durham from the National Science Foundation for the initiative and perseverance in making this study happen. Fred Thompson and K. Rajurkar from NSF also deserve acknowledgments for their active roles in the study. We also thank Geoff Holdridge of WTEC for the operational management of this study. This paper is a result from the work sponsored by the National Science Foundation and the Department of Energy under NSF Cooperative Agreement ENG-9707092, awarded to the International Technology Research Institute at Loyola College, MD. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the US government, the authors' parent institutions, or Loyola Tech.

References

- [1] EPA, 1998a, *TRI Total Releases*, (see www.epa.gov/tri).
- [2] Park, S. H., and W. C. Labys, 1998, *Industrial Development and Environmental Degradation: A Source Book on the Origins of Global Pollution*, Edward Elgar Pub. Ltd.
- [3] WTEC, 2000, *Environmentally Benign Manufacturing*, WTEC Panel Report, Baltimore, MD, Loyola College.
- [4] Moll, S., and Gee, D, eds., 1999, "Making Sustainability Accountable: Eco-efficiency, Resource Productivity and Innovation," *Proc. of the Fifth Anniversary of the European Environment Agency Workshop*, October 1998.
- [5] Skillius, A., and Wennberg, U., 1998, *Continuity, Credibility and Comparability: Key Challenges for Corporate Environmental Performance Measurement and Communication*, International Institute for Industrial Environmental Economics at Lund University.
- [6] Roodman, D. M., 2000, "Environmental Tax Shifts Multiplying," *Vital Signs 2000*, Brown, L. R., Renner, M., and Halwell, eds., W. W. Norton and Company, New York.
- [7] EEA, 2000, *Environmental Taxes: Recent Developments in Tools for Integration*, European Environment Agency, Environmental Issue Series, No. 18.
- [8] Porter, M., and van der Linde, C., 1995, "Toward a New Conception of the Environment Competitiveness Relationship," *Journal of Economic Perspectives*, 9(4), pp. 97-118.
- [9] Portney, P. R., 1998, "Counting the Cost: The Growing Role of Economics in Environmental Decision-making," *Environment*, 40(2), pp. 14-18, 36-38, March.
- [10] Hawken, P., Lovins, A., and Hunter Lovins, L., 1999, *Natural Capitalism: Creating the Next Industrial Revolution*, Rocky Mountain Institute.
- [11] Dowell, G., Hart, S., and Yeung, B., 2000, "Do Corporate Global Environmental Standards Create or Destroy Market Value?" *Manage. Sci.*, 46(8), pp. 1059-1074.
- [12] Darnay, A., ed., 1998, *Manufacturing USA. Industry Analyses, Statistics & Leading Co*, 6th ed. Gale Publishers.
- [13] EPA, 1998b, *TRI On-site and Off-site Releases by Industries* (see www.epa.gov/tri/tri98/data/datasum.htm).
- [14] Mattus, J., and Sheng, P., et al. 1997, *A Frame Work for Analyzing Energy Efficient Injection Molding Die Design*, CSM Report #96-09, Engineering Systems Research Center U.C. Berkeley.
- [15] Allen, D. T., 1995, *Clean Chemical Manufacturing Technologies: Current Practices and Long Term R & D Priorities*, Report submitted to the US Congress, Office of Technology Assessment.
- [16] ARC, 1997, *Proceedings of Society of Plastic Engineers 4th Annual Recycling Conference*.
- [17] Gerngross, T. U., and Slater, Steven C., 2000, "How Green are Green Plastics?" *Sci. Am.*, pp. 37-41, August.