"TECHNOLOGY WEDGES" FOR IMPLEMENTING GREEN MANUFACTURING

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ABSTRACT

Environmental issues in manufacturing are receiving increasing attention as part of the global concerns about environmental impacts and energy efficiency. This paper outlines a strategy using the "technology wedge" concept to address the improvement of manufacturing processes towards the goal of green manufacturing. After defining the nature of the wedges and how to assess their impact, an example of a potential wedge technology is reviewed. The wedge concept can be useful in assessing directions for new process developments in manufacturing as well as improving existing processes.

INTRODUCTION AND BACKGROUND

Increasingly, concerns about the availability and cost of energy and raw materials, the impacts of industrial activity, and the efficient re-use of consumer products at the end of their life are driving efforts towards "green manufacturing." This is part of a much larger international concern over the overall accomplishment of sustainability in design and manufacturing. Sustainability, as defined here, implies a level of resource utilization that is very comprehensive in its scope. It must be in accord with a level necessary to insure that, over time, the resource will a) not only be available; but b) demand is reduced to approach a level of what is naturally sustainable. That is, the "gap" between current use and sustainable use must be understood. This is a hard measure to meet but it is, ultimately, what is necessary.

The topic of "green business" is very popular today in the business and general press. Companies from *GE* (with its "Ecomagination" campaign) to *Wal-Mart* (with its sustainable supply chain for some products) are finding it both profitable and responsible to promote green products. Some, like *Toyota*, even mention the need for the entire manufacturing process, including the supply chain, to be green. Companies like *Interface Carpet* have aggressively tackled the problem relative to their production and made impressive progress that, at the same time, is on the road to facilities and production that meet the full definition of sustainable manufacturing. Not surprisingly, the basis of claims of “green-ness” and level of commitment vary widely over a wide range of products (Hawken 1993).

It is not the goal of this paper to rate the seriousness, or the “sensitivity-to-public-needs,” of any particular manufacturing company or product that is sold. Rather, it is our goal to help define a methodology by which manufacturing engineers, when tasked to manufacture products in a green manner, can accomplish this within the constraints of the particular product or process being manufactured.

A short introduction to green manufacturing is presented followed by a review of the elements and scope of the system that should logically be included in any discussion of green manufacturing. The concept of “technology wedges” and how they might be applied to identifying opportunities for environmentally benign manufacturing and integrating solutions with existing processes or supply chains is discussed. Finally, an example of a canidate technology wedge drawn from the work of the authors is presented.

GREEN MANUFACTURING

It is not possible here to offer a complete review of the literature on green manufacturing and related topics. A number of very comprehensive studies have been made detailing the work ongoing in the world relative to the first attempts at green production. The WTEC report, for example, discussed the status of environmentally benign manufacturing in the US and abroad (WTEC 2000; Allen et al. 2002). Integration of green components and analysis into manufacturing systems was considered early on (Sheng et al. 1995). Anastas and Zimmerman (2003) address link in design considerations. Some researchers have addressed specific parts of the manufacturing process in more detail with success, e.g. minimum quantity lubrication/dry machining (Filipovic and Sutherland 2005; Zimmerman et al. 2004) which is now being implemented in a number of manufacturing operations internationally. The National Science Foundation has organized workshops to make the research community more aware of the overall issues and opportunities for “environmentally benign design and manufacturing” or EBDM (and an EBDM Community Web has been created) (EBDM 2006). These specific accomplishments are often referred to as “technology wedges” that form part of a comprehensive solution. The wedges are explained in more detail in the next section.

A schematic of the green elements of design and manufacturing is shown in Figure 1, modified from Ishii (1999). The “life cycle” of the product from design to recycling or reuse at end of life must be considered. The figure distinguishes between the design of a product and the processor systems that makes the product. Of importance is that both the design of the process and how the process operates to manufacture the product are considered. Substantial opportunities exist in the design of machines that make products (for example,

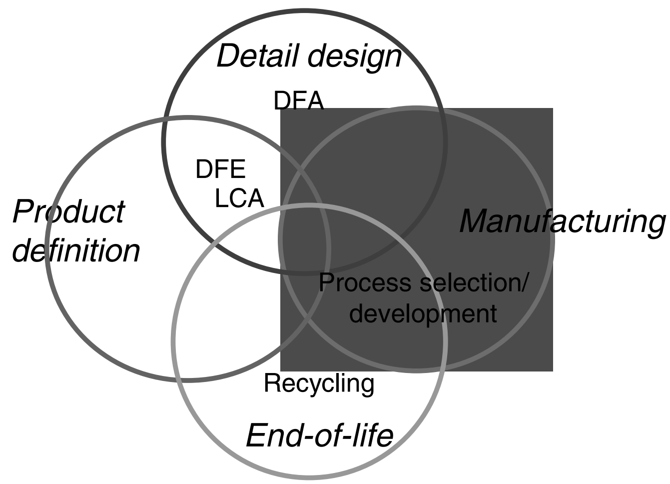

FIGURE 1. SCHEMATIC OF “GREEN” ELEMENTS OF DESIGN AND PRODUCTION, MODIFIED FROM ISHII (1999).

machine tools (see Taniguchi et al. 2006) as well as in their productive operation (macro and microplanning, for example, see Srinivasan and Sheng 1999a,b). Although not specifically shown in Figure 1 these elements include the supporting supply chain companies as well.

As we seek green manufacturing practices it is necessary to consider the environmental impact of all the elements in a product’s life cycle as shown in Figure 2 (Horvath 2003). It covers the broadest scope possible from the original source of raw materials (including mining costs) to eventual disposal of the used product. Each element includes waste (or non-utilized resources and by-products). The energy and resources consumed in each of these stages of

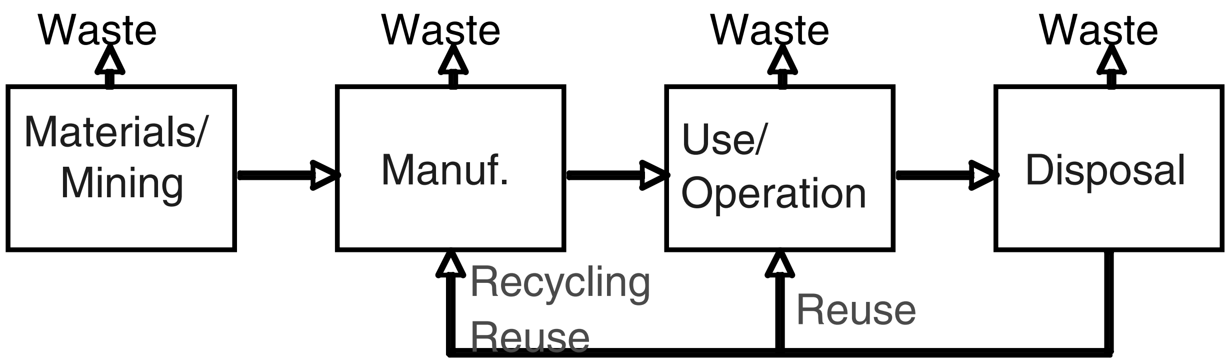

FIGURE 2. LIFE CYCLE CHAIN ELEMENTS FOR ENVIRONMENTAL IMPACT ANALYSIS, AFTER HORVATH (2003).

the process, and the waste output, will “count against” any benefits of the new product or machine resulting from the process. To be effective, there must be a net energy, resource or environmental impact savings over the life of any product or process produced in an “environmentally benign” manner to meet the sustainability definition. Colloquially, it can be said: “If you consume as much resource in manufacturing a product as you save in use of the product you have not succeeded!” This requires careful accounting for the impact of all the process chain elements and that is often not easy to do.

The individual processes represented by the boxes in Figure 2 can be exploded as seen in Figure 3, after Horvath (2003). Each process is comprised of many sub-processes and sub-systems each having, on its own, sub processes and systems. Thus is the nature of manufacturing and the bill of materials (BOM) reflects the diversity of the product and the source of the materials.

The question is, then: “Where is the most efficient point in this complex broad scope to introduce improvements or enhancements relative to our goal of implementing environmentally benign manufacturing?” Tools exist, for example, life cycle engineering analysis. Please see Hendersen (2006) for a detailed description of the state of the art that allow the determination of the “environmental cost” of each element. Sometimes these costs are not very accurately computed due to the sources of data, but they provide a valuable start. A good example, besides those in Hendersen cited above, is Williams et al. (2002) describing the energy and materials that go into a modern semiconductor device.

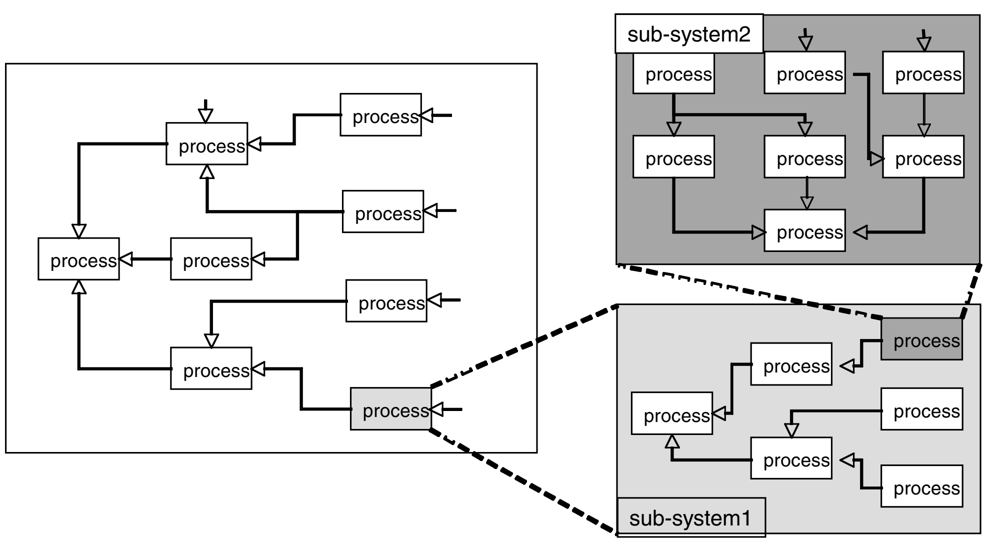

FIGURE 3. BREAKDOWNS OF SUBELEMENTS IN MANUFACTURING SYSTEM CONTRIBUTING TO THE FINAL PRODUCT, AFTER HORVATH (2003).

Other tools include the environmental value system analysis, EnV-S. This has been successfully applied to semiconductor processes, for example chemical mechanical planarization (CMP). It analyzes trade-offs between system components for waste treatment (a sub-system of the CMP process) to achieve the highest environmental enhancement while minimizing cost per piece (another wedge) (see, for example, Krishnan et al. 2004).

With this level of analysis *for the entire system of production*, a reasonable determination can be made of the cost/benefit of proposed changes. And, the goal of the changes or enhancements is to provide some improvement in the overall operation of the process or system. This can be implemented as part of agent-based process planning where an 'environmental agent' provides feedback on issues that affect the environmental performance of the process or system (Dornfeld and Wright 1997; Dornfeld et al. 1999). The concept of wedges and their role in the improvement of the system is detailed next.

MANUFACTURING TECHNOLOGY WEDGES

A paper in *Science* in 2004 describes the concept of "stabilization wedges" with respect to technology that could solve the climate problem (with respect to fossil fuels) for the next 50 years using current technology (Pacala and Socolow 2004). The idea, shown in Figure 4 from that reference, illustrates the concept. The "gap" between the current trends in fossil fuel emissions relative to the atmosphere's capability to accommodate emissions is shown in green in graph A. This is a similar gap to that defined earlier relative to sustainable design and manufacturing (normal consumption *vs.* sustainable consumption). Graph B in Figure 4 illustrates a set of "wedges." Each individual wedge represents the ability of some existing current technology to reduce, on its own, some portion of fossil fuel emission. Then, summed together, these wedges provide the necessary reduction in emissions to achieve an overall "sustainable" situation. The acronyms in figure A are BAU – business-as-usual and WRE500 – referring to CO_2 stabilization at 500ppm by 2125.

The question is whether or not this strategy could be employed in manufacturing to accomplish environmentally benign manufacturing processes. There is, as noted in the introduction, an increasing interest in developing process enhancements that contribute to reducing an environmental impact. As yet, there is no strategy to coordinate a set of enhancements and new capabilities that will, combined, render a process "sustainable" as in the case of the fossil fuel emission example.

There are some interesting possibilities. With the development of new manufacturing technologies for micro-scale and nano-scale manufacturing, as well as the various alternate energy sources being pursued (from fuel cells to photo-voltaics) attention will need to be paid to ensure that any new processes will have a positive effect in an environmental sense. That is; wedges must be design ed to be "net-positive." An improvement in one element of a process or system of manufacture cannot be at the expense of another segment of the cycle. This is specially complicated with the complex supply chains employed today. Continuous improvement is as valid here as in other areas of manufacturing. We strive to remove "wasted time and effort." Why not also try to do this for energy/consumables/waste? In this paper we

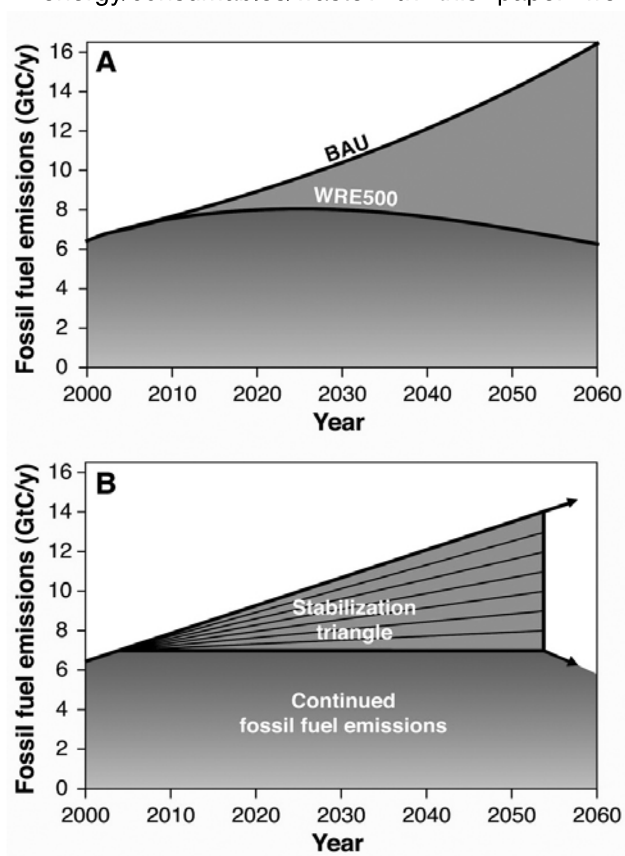

FIGURE 4. ILLUSTRATION OF "STABILIZATION WEDGES" FROM PACALA AND SOCOLOW (2004).

propose that "technology wedges" – analogous to "stabilization wedges" – offer a framework and potential metric for addressing these energy challenges. The specifics of that metric need a lot of development based on discussion in the community.

There are a number of *fundamental rules* which govern how wedge technology can be employed in manufacturing. In no particular order, they are:

Rule 1. the cost of materials and manufacturing (in terms of energy consumption and Green House Gas (GHG) emissions, etc.) associated with the wedge cannot exceed the savings generated by the implementation of the wedge (or wedges) over the life of the process or system in which it is employed.

Rule 2. the technology must be able to be applied at the lowest level in the process chain. For example, in Figure 2 this would be at one of the root processes in a subsystem.

Rule 3. the cost and impact of the technology must be calculable in terms of the basic metrics of the manufacturing system and the environment. That is, cost and impact must be expressible in units of dollars (or euros, yen, yuan, etc), carbon equivalent, global warming gas creation or reduction, joules, cycle time and production rate, quality measures, lead time, working capital and so on *relative to present levels* of consumption, use, time, etc.

Rule 4. the technology must take into consideration societal concerns along with business and economy, see Hawken (1993) for example, and

Rule 5. there must an accompanying analytical means or design tool so that it can be evaluated at the design stage of the process or system. It must be an integrated approach.

These rules, when applied, will insure a balanced and honest appraisal of the impact of the technology from an environmental perspective and also insure the rules are feasible from a business perspective. This will avoid creation of anomalies in the supply chain caused by a local gain which yields a global net loss. Many examples of a net loss currently exist in society, such as with so-called "high tech/low cost" products, some of which operate efficiently, but which have short useful lives. The consumer "learns" to expect this and, thus, expects to replace the product in a short time. This trend destroys a tremendous amount of product value and resources and, worse, it encourages increased environmental damage. The life cycle of such "throw-away" products is often not considered in the design, fabrication, or use.

EXAMPLE OF WEDGE TECHNOLOGIES FOR MANUFACTURING

It is instructive to review an example that could be considered a "wedge technology" in manufacturing. As mentioned earlier, there are no complete sets of wedges as proposed in the fossil fuel example. The closest so far, perhaps, is the experience of *Interface Carpets* , see Interface Carpet website. There, thanks to a dedicated and aggressive effort, the evidence of reduction, re-use, and increased efficiency is seen in all three of areas of economy (reduced cost per unit of manufacture, here a square yard of carpet), environment (reduced generation of greenhouse gases per unit of production) and society (where a measure used is an impressive re-direction of material from landfills to re-use; this is in addition to the reduction in global warming gases already noted).

The example we have chosen to review here is at the level of the individual sub-process step seen in Figure 3 and is derived from our "basic manufacturing" research.

<u>Wireless Sensor Technology Wedge</u>

Certain technologies such Wireless Sensor Networks (WSNs) offer solutions that address several of the above Rules. On the left of Figure 2, mining, raw material acquisition, and primary processing usually consume considerable amounts of energy and also have potential environmental impacts. Also, in the second box of Figure 2, traditional machine tools and automation systems are often operating inefficiently. However, with corrective "condition based monitoring" they can utilize less energy, require less maintenance, and function for more years hence providing a net-gain in global sustainability. Reduced energy, less maintenance, and longer lasting machinery thus have both "green" and "profitability" impacts.

Industrial metallurgical operations (box #1 in Figure 2) are ripe for such wireless monitoring, with aluminum smelting being an obvious choice given its inherent thermodynamic inefficiency and fluoride pollutants. Figure 5 shows the experimental technique being used to measure the temperature of the gas emanating from the exhaust ducts of standard aluminum smelters (Schneider et al. 2006). Dando (2002) proposed that there is a fairly direct correlation between the temperature of the exhaust gases the evolution rates of fluorinated hydrocarbon (HF) – an obvious greenhouse gas.

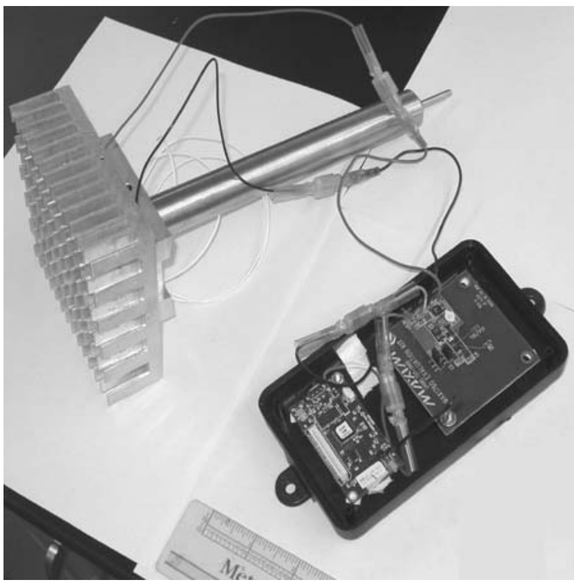

FIGURE 5. TEMPERATURE SENSOR (UPPER PROBE) CONNECTED TO A WIRELESS SENSOR NODE (LOWER PCB) AND CONDITIONING ELECTRONICS WITH HEAT SINK UTILIZING THE SEEBECK EFFECT TO POWER THE SYSTEM (SCHNEIDER ET AL. 2006).

The individual smelting cells with the highest gas exit temperatures (~160^{o} C) exhibited fluoride (HF) evolution rates that were 2-3 times higher than those of smelting cells with the lowest exhaust duct temperatures (~100^{o} C) and such temperatures could be readily detected by a hand held infra-red temperature device being used by an operator on the factory floor. This task could not be readily justified as an ongoing 24/7 operator function. As a result, the inexpensive device (technology wedges) shown in Figure 5 can provide a permanent way of measuring the temperature of the gases exiting the ducts -- then allowing operator diagnosis and likely adjustment of the cell voltage to minimize green house gas emissions.

The second WSN example (for box #2 in Figure 2) relates to machine monitoring. Wireless sensor networks can make an impact on many aspects of *predictive maintenance* and *condition based monitoring*. Figure 6 shows that these two topics build upon each other in terms of information content and complexity, and hence become increasingly useful to overall efficiency. *Predictive maintenance* was actually shown in the foregoing aluminum smelting example, where the application of a WSN enabled increased frequency of sampling and hence GHG (HF) reduction. *Condition-based monitoring applications* allow even more sensing points, more precise locations of sensors, and thus a higher degree of automation.

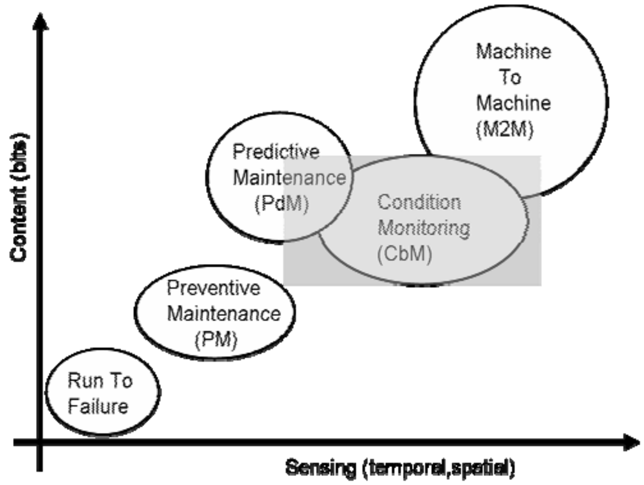

FIGURE 6. GRAY AREA DENOTES WHERE WSNs ARE APPLICABLE FOR ENERGY SAVING.

Predictive maintenance for green manufacturing. Predictive maintenance is closely related to energy management practices in the manufacturing sector. Since manufacturing accounts for approximately one third of the U.S. national primary energy consumption (EIA 2006), high value is placed on each additional percentage of energy efficiency. Lu et al. (2005) for example, describe how WSNs enable factory wide maintenance and energy management of small electric motors.

Condition based monitoring. WSNs can also be used for condition-based monitoring of machinery, especially the monitoring of overall vibrations – hence leading to longer life of machinery and net-savings in Figures 1-3.

SUMMARY AND FUTURE

The challenge of employing a “set of wedges” addressing a single process chain and affecting energy or consumable use throughout that chain is daunting. We did not present an integrated solution – rather, some examples based on sensing of critical process conditions to show potential. It is, in our minds, a next step, and great opportunity, to consider the technologies the manufacturing community is researching as wedges that, in combination, can have a large impact.

The WTEC panel summarized their work in Allen et al. (2002) stating that “A broader vision that includes environmental considerations as an integral part of the entire system of doing business and engineering is necessary.” They continue by stating that “There was no evidence that the EBM [environmentally benign manufacturing] problem is solvable by a “silver bullet” technology.” The thesis of this paper is that technology wedges, as defined and illustrated here, in combination with design tools to aid engineers in assessing the impact of the wedges (economic, societal, environmental) can give manufacturing engineers tremendous leverage towards developing and implementing solutions that will render environmentally benign processes. A number of researchers are working on these “wedges”. The methodology for integrating them and assessing their effectiveness relative to sustainable manufacturing remains to be determined and tested.

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REFERENCES

Allen, D., D. Bauer, B. Bras, T. Gutkowski, C. Murphy, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston, and E. Wolff (2002). “Environmentally benign manufacturing: Trends in Europe, Japan and USA” *Trans. ASME, J. Manufacturing Science and Engineering*, 124, pp. 908-920.

Anastas, P. and J. Zimmerman (2003). “Design through the 12 principles of green engineering.” *Environ. Sci. Technol. A-Pages*, 37(5), pp. 94A-101A.

Dando, N. (2004). “Using fume dust temperatures for minimizing open holes in pot cover.” *Light Metals*, pp. 245-248.

Dornfeld, D. and P. Wright (1997). “Process planning for agent-based precision systems.” *Trans. of NAMRI/SME*, Vol. 25. pp. 359-364.

Dornfeld, D., P. Wright, F. Wang, P. Sheng, J. Stori, V. Sundarajaran, N. Krishnan, and C. Chu (1999). “Multi-agent process planning for a networked machining service.” *Trans. of NAMRI/SME*, Vol. 27, pp. 191-196.

EIA (2006). Energy Information Administration, “Annual Energy Outlook 2006.” Report #:DOE/EIA-0383(2006). U.S. Department of Energy, Feb. 2006.

EBDM website, http://www.ebdm.us/.

Filipovic, A. and J. Sutherland (2005). “Development of magnetostrictive tool-holder for dry deep hole drilling.” *Trans. of NAMRI/SME*, Vol. 33, pp. 437-444.

Hawken, P. (1993). *The Ecology of Commerce*. New York: Harper Collins.

Henderson, C., S. Lave, and S. Matthews (2006). *Environmental Life Cycle Assessment of Goods and Services*, Resources for the Future, Washington, DC.
Horvath, A. (2003). Course notes, personal communication.

Interface Carpet sustainability website: http://www.interfacesustainability.com/

Ishii, K. (1999). "Incorporating end-of-life strategy in product definition." EcoDesign '99: First Int'l Symp. on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan.

Krishnan, N., S. Raoux, and D. Dornfeld (2004). "Quantifying the environmental footprint of semiconductor process equipment using the environmental value systems (EnV-S) analysis." *IEEE Trans. Semiconductor Manufacturing*, 17, 4, pp. 554-561.

Lu, B., T. Habetler, R. Harley, and J. Gutierrez (2005). "Applying wireless sensor networks in industrial plant energy management systems – Part I: A closed-loop scheme." *Sensors, 2005 IEEE*.

Pacala, S. and R. Socolow (2004). "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies." *Science,* 305: pp. 968-972.

Schneider, M., J. Evans, P. Wright, and D. Ziegler (2006). "Designing a thermoelectrically powered wireless sensor network for monitoring aluminum smelters." *Proceedings of the Institute of Mechanical Engineers, Part E: Process Mechanical Engineering,* Vol. 220, JPME67, pp. 181-190.

Sheng, P., D. Dornfeld, and P. Worhach (1995). "Integration issues in green design and manufacturing." *Manufacturing Review*, Vol. 8, No. 2, pp. 95-105.

Srinivasan, M. and P. Sheng (1999a). "Feature-based process planning for environmentally conscious machining – Part 1: microplanning." *Robotics and Computer Integrated Manufacturing*, 15, pp. 257-270.

Srinivasan, M. and P. Sheng (1999b). "Feature-based process planning for environmentally conscious machining – Part 2: macroplanning." *Robotics and Computer Integrated Manufacturing*, 15, pp. 271-281.

Taniguchi, M., Y. Kakinuma, T. Aoyama, and I. Inasaki (2006). "Influences of downsized machine tools on the environment." Proc. MTTRF 2006 Meeting, San Francisco.

WTEC (2000). *Environmentally Benign Manufacturing,* WTEC Panel Report, Baltimore, MD, Loyola College.

Westkamper, E. (2003). "Assembly and disassembly processes in product life cycle perspectives." *Annals of the CIRP*, 52, 2, 579.

Williams, E.D., R.U. Ayres, and M. Heller (2002). "The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices." *Environmental Science and Technology*, 36 (24), pp. 5504-5510.

Zimmerman, J., K. Hayes, and S. Skerlos (2004). "Influence of ion type and concentration on the emulsion stability and machining performance of two semi-synthetic metalworking fluids." *Environmental Science and Technology*, Vol. 38, pp. 2482-2490.