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Sustainable Manufacturing – Greening Processes, Systems and Products

Author
Dornfeld, David

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Edited by
Prof. Dr.-Ing. habil. Prof. E. h. Dr.-Ing. E. h. Dr. h.c.
Reimund Neugebauer

Fraunhofer Institute for Machine Tools and Forming Technology IWU
Reichenhainer Straße 88, 09126 Chemnitz, Germany
e-mail: info@iwu.fraunhofer.de

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Sustainable Manufacturing – Greening Processes, Systems and Products

Dornfeld, D. A
University of California, Berkeley, CA, USA

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Abstract

Implementing green manufacturing, as the first step towards sustainable production, has been growing in interest and importance over the last few years. The opportunities for developing advanced manufacturing capabilities while, at the same time, reducing the impact of manufacturing on energy use, water and resource consumption and, overall, green house gas emissions and carbon footprint are numerous. This paper reviews the background, vocabulary and motivation for green manufacturing and highlights the competitive opportunities for manufacturers who embrace, seriously, this growing movement. The terms "green" and "sustainable" are defined in a manufacturing context, metrics and tools for assessing manufacturing are described, and some concrete examples of how to begin and what are others doing are given. Some of the future directions of green manufacturing are discussed.

1 *Background, motivation and drivers*

1.1 The move to green manufacturing

There are many challenges facing the word today and energy and the environment have risen to be among the top concerns. These concerns are usually associated with a larger overarching challenge – sustainable development. The portion of this that most directly impacts manufacturing is often referred to as green, or sustainable, manufacturing. Implementing green manufacturing is often considered as the first step towards sustainable production. The opportunities for developing advanced manufacturing capabilities while, at the same time, reducing the impact of manufacturing on energy use, water and resource consumption and, overall, green house gas emissions and carbon footprint are numerous.

In this paper, the terms "green" and "sustainable" will first be defined in a manufacturing context and the metrics and tools for assessing manufacturing will be described. Finally, some concrete examples of how to begin and what are others doing are given and some aspects of the future direction of green manufacturing discussed. But first, what is driving industry in this direction?

For industry, these concerns have come to the forefront in a number of ways. In no particular order, these include:

- Pressure from Government; This is from both individual governments at the state (like California) or national level as well as regional governments, like the European Union, for example. Governmental pressure is often implemented as:
  - regulations; recently a number of requirements for product performance, material composition, energy usage, etc. have been implemented.
  - penalties for lack of compliance which add cost of operations until the cause is resolved.
  - tax benefits and other incentives for complying or taking action
- Interest in Efficiency/Reduced Cost of Ownership (CoO); reducing waste is a basic element of manufacturing.
- Scarcity of Resources/Risk; for processes or systems that rely on continuous supply of basic resources, including materials and water, reducing the dependency on these resources as well as reduced energy can reduce or eliminate risk from interrupted supplies or large cost fluctuation due to varying supply or demand or currency exchange rates.
- Continuous Improvement; improving process efficiencies is a key element.
- Pressure from Society/Consumers/Customers; consumers are increasingly aware of the need to reduce environmental impact of products, including their manufacture. For manufacturing machinery, the customer can be other manufacturers who are focused on reducing waste and consumption of energy and resources.

- Pressure from Competitors; in response to the societal and consumer drivers listed above, many companies use their efforts and advances in reducing the environmental impact and consumption of their products or systems as part of marketing strategies that show both reduced cost to operate and environmental benefits as an advantage.
- Maintain Market Leadership; if you are already known as a leader in technology or performance you can add environmental leadership to your list.
- Understand Supply Chain Effects (what's happening outside of your facility?); this is the hidden part of manufacturing – the part you don't control directly. Many examples of problems related to materials or other effects from unknown links in the supply chain exist. Most of these were unknown to the final producer and caused substantial problems.

1.2 Major opportunities

From the perspective of manufacturing, these drivers listed above offer some tremendous opportunities. First off, all future energy, transport, medical/health, life style, dwelling, defense and food/water supply systems will be based on increasingly precise elements and components – that is, precision manufacturing. In addition, given the demand of an environmentally aware consumer, the products that evolve (autos, consumer products, buildings, etc.) with minimum energy consumption and as sustainable as possible, will offer some interesting manufacturing challenges – challenges that will drive manufacturing technology advances.

A number of alternate energy supply systems are under development from solar to fuel conversion systems to more efficient fuel cell power systems and solar panels. In many cases, the "scalable" manufacturing technology to go from bench top to full deployment is not yet developed. More conventionally, machine tools using less energy, materials, and space are in increasing demand and will require new control capabilities and re-manufacturing features. These machines will be used in increasingly efficient factory operations where the systems of production are optimized for both productivity and minimum energy and resource use. Finally, the need to comply with government regulations will contribute to a more level playing field for implementing these advances. These can all lead to competitive advantages and technology advancement if addressed by the machine and tool manufacturers and industry.

2 Defining green and sustainable

2.1 What does sustainable mean?

We are all familiar with the Brundtland Commission definition of sustainable development - "Sustainable development is development that meets the need of the present without compromising the ability of future generations to meet their own needs" [1]. This does not really speak to manufacturing but makes the key point that we need to at least "do no harm." A more contextual definition of sustainable manufacturing is adapted from the US Department of Commerce as "the creation of manufacturing products that use materials and processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [2]. Green manufacturing is a first step towards sustainability.

These first steps can be thought of as "technology wedges" after a concept proposed by Pacala and Socolow to address the big gap between the present trajectory and impact of CO_2 on the atmosphere (business as usual – BAU) and a sustainable level – and how to close this gap in 50 years [3]. They argue that, rather than trying to find one "silver bullet" to correct this increasing mismatch between what we need and what we are doing, we should concentrate on "technology wedges" – small advances and improvements that, when added up, have the effect of a large change in the way we do business. Their wedges include efficiency improvements, carbon capture and storage from power plants, renewable power, etc. The specific wedges they propose are not the main interest here. But, the idea has real merit.

These wedges make more sense in the context of manufacturing and sustainability. We can visualize sustainability as a relationship between consumption or impact as part of normal business practice compared to a "sustainable level." For example, in California we store rainfall during the winter months as snow in the Sierra Nevada mountains. The amount of snow determines the amount of water we have to use in the next season for residential, commercial and agricultural use. If we use water at a rate that will exhaust the supply before the next rainfall – that is not a sustainable situation. We are using too much and should find a way to conserve or reduce usage. We could make the same argument for impact, for example, green house gas generation. The atmosphere has a certain capacity to accommodate green house gases. Exceeding that risks a build up that will endanger future generations according to the predictions of atmospheric scientists.

We can illustrate this as seen in Figure 1 below. The figure illustrates the normal trend of consumption or impact over time. A small reduction of either one results in a reduced rate of impact but does not provide enough change to achieve a sustainable situation. The application of technology wedges to, collectively, bridge the gap between present rate of consumption or impact and a sustainable level is illustrated with the green triangles. With sufficient wedges, the gap can be closed.

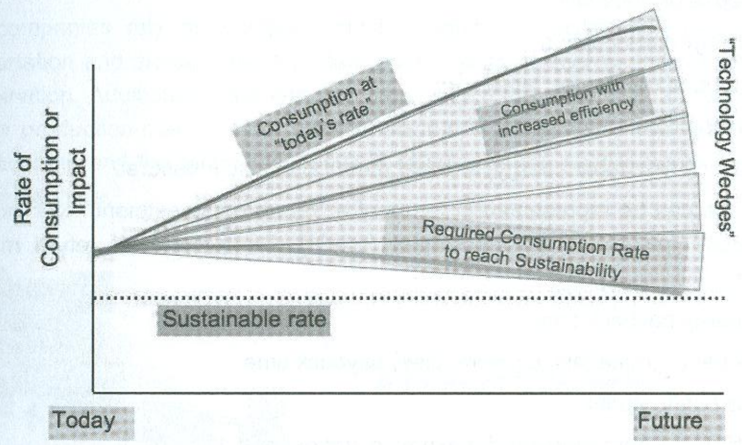

Figure 1: *Illustration of sustainable consumption and technology wedges*

It is our role to come up with the wedge technologies. Individual wedges might be considered as "green" manufacturing steps. If there are sufficient greening steps we can achieve sustainable manufacturing. There are some general rules that should be considered when evaluating green technology solutions (wedges). These are beyond the scope of this paper but can be reviewed in [4]. Since that paper was written some refinement of these basic rules could be added but, overall, they are applicable.

2.2 Metrics for assessing green manufacturing

A metric is defined here as a type of "measurement used to gauge some quantifiable component" of performance, like return on investment (ROI) for a company's revenues, etc. These metrics are used by engineers for analyzing information and data to enable better decision making, including trade-offs among several alternatives. For green manufacturing these metrics could include:

- Global warming gas emission (e.g. CO_2, methane CH_4, N_2O, chlorofluorocarbons, CFC's)
  - per capita
  - per GDP
  - per area/nation
- Recyclability (or percent recycled)
- Reuse of materials
- Energy consumption
- Pollution (air, water, land)
- Ecological footprint - "fair share" - footprint
- Exergy (available energy) or other thermodynamic measures

And, these can be represented in terms of a "return on investment" - for example, greenhouse gas return on investment (GROI). Other forms of return measure include:

- Energy payback time
- Water (or materials, consumables) payback time
- Carbon footprint
- Efficiency improvement (for example, wrt exergy)

For green manufacturing these need to be linked to traditional design and manufacturing parameters. And they need to be assessed over all three scopes of ISO 14064 (1- direct emissions from on-site or company owned assets, 2- indirect emissions created on behalf of the company from energy generation or supply, 3- all others resulting from your business operation including business travel, shipping of goods, resource extraction and product disposal).

3 Opportunities and challenges

3.1 Strategies for greening manufacturing

3.1.1 Product life cycles

The first consideration in addressing green manufacturing strategies is to determine the extent of the product chain being addressed. Figure 2 illustrates the entire life cycle from extraction of material through material conversion (for example, creating

sheets and bars), manufacturing (forming, forging, cutting, assembly, etc), transport and distribution, use and, eventually, reuse/remanufacture, recovery or disposal. This is important since many consider only the middle "manufacturing" stage as the domain of interest. In fact, green manufacturing covers the entire spectrum since the embedded energy in the material used for production of machinery is dependent on the type and source of the material. Conversion adds energy and uses resources.

Most companies rely on complex supply chains and distribution networks so transportation and storage are important components of energy and resource use determination. Additionally, the end user, specially if the product is a machine tool or other production machinery or system, plays a significant role. So, really, green manufacturing and the technology wedges referred to are applicable all along this product life cycle.

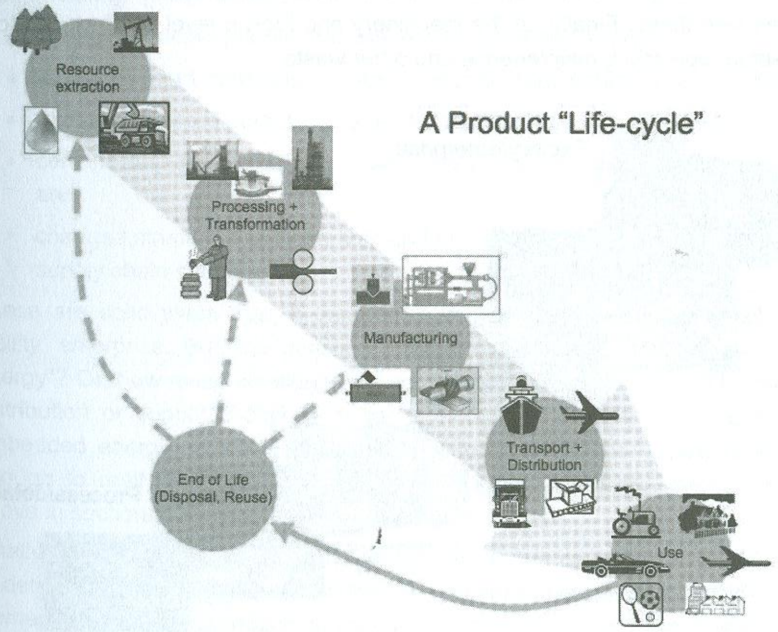

Figure 2: Product life cycle

3.1.2 "Google earth view" of manufacturing

Another axis of green manufacturing relates to the "control volume" over which metrics are applied and potential green technology wedges are implemented. One interesting way to view this is to think of the manufacturing enterprise as viewed from a "Google earth viewer" – meaning one can look deeper into the enterprise, Figure 3 (images, [5]). This view shows, starting at the factory level, the various 'scales" of systems and processing from the enterprise level, to the factory level, to the production line in the factory, to individual machines and then down through tooling and setup on the machine. Finally, we see the tool/work process interface. At each of these levels opportunities exist for green technology wedges.

More specifically, at the manufacturing level this can include plant/HVAC, food service/cafeteria, human relations and other office functions, management, packaging and shipping, and associated waste. At the processes and systems level this includes energy, water, materials, consumables, compressed air and waste associated with these. Finally, at the machinery and tooling level this includes tool design, setup, operation, maintenance and other waste.

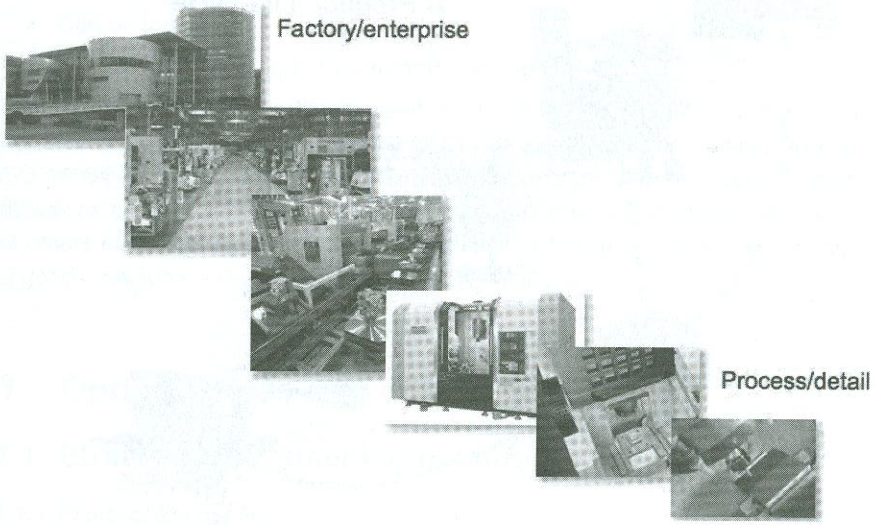

Figure 3: *"Google earth" view of manufacturing*

3.2 Solutions in the manufacturing space

The solutions (or "wedges") that can be applied to the range of levels of manufacturing as shown in Figure 3 are generally categorized as either: technology (improve the manufacturing process or system), material (use lower impact materials), or energy (use cleaner energy sources or recover energy). This relates to improving the efficient use or application of energy in the process, system and enterprise. An underlying requirement is that any potential solutions be cost effective as well and do not adversely affect production capability, throughput, quality, process availability, etc.

Allwood defines sustainable manufacturing as "Developing technologies to transform materials without emission of greenhouse gases, use of non-renewable or toxic materials or generation of waste" and he has proposed a set of five options for sustainable manufacturing. We can adapt these towards "greening manufacturing" [6]. These are:

- create products/systems that use less material and energy
- substitute input materials: non-toxic for toxic, renewable for non-renewable
- reduce unwanted outputs: cleaner production, industrial symbiosis
- convert outputs to inputs: recycling and all its variants (meaning zero waste), and
- changed structures of ownership and production: product service systems and supply chain structure

These are solid steps that, if pursued, can lead to a greener process, system, facility, enterprise. But, the question arises - how much "less material"? or "less energy"? Or, how much substitution is needed? How much do I need to change my distribution or supply chain? How can I monitor my supply chain to reflect the embedded energy or material utilization? Basically, how do I know how much is enough to really make a positive change? That's where the metrics discussed above in section 2.2 come into use.

Finally, with the metrics and analytical tools to do the required "trade-off" analyses to determine if the "cure is worse than the disease" we need to consider the cost element. All previous major advances in manufacturing have been achieved because someone put a monetary value on some aspect of the process or system that had been previously overlooked or considered as a benign element. Each of these advances occurred because of a realization that an improved system of manufacturing could be attained if the system was "designed and optimized" based on an understanding of some new criteria. These criteria included more control of the process and standardization introduced by Henry Ford, better use of manufacturing machinery and increased productivity introduced by Taiichi Ohno, and reduced inventory and buffer stocks for quality production, the ideas of Edwards Deming and Ohno, among others. And, they all had a monetary value that could be assigned to do the required "cost-benefit" analysis. Hence, we need to be able to "monetize" the value of sustainability to drive the implementation of these "wedges."

4 Focus on manufacturing processes, systems and machines

4.1 Scale of effects

The view seen in Figure 3 indicates that at many different levels there are opportunities for greening manufacturing. In this section we'd like to take a closer look at some of the details.

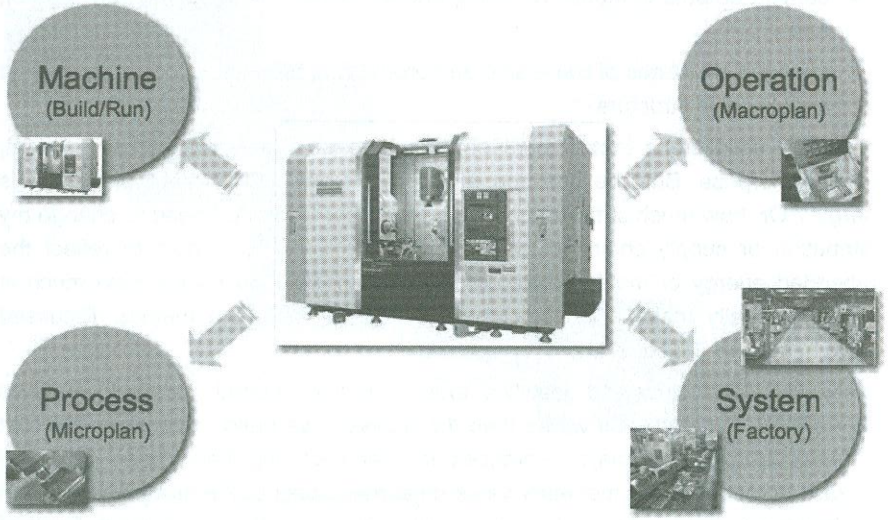

Figure 4: *Effects at different scales*

First, we can explore the level of process and machine, Figure 4. Illustrated here are four potential levels of technology – the machine tool (and how it is built, and operated), the "macroplan" operation (or the sequence of operations on the machine(s) in production), the "microplan" operation (or the detailed process conditions for each step in the macroplan) and, finally, the systems of machines and how they operate together in the line or factory.

At each of these levels there are a number of specific improvements or enhancements to be considered. For example, at the machine level, one can insure that machine construction insures minimum embedded energy, materials, resources per unit of performance (positioning accuracy, speed, thermal stability, etc. in machine tool frame and components), minimum operating energy (hydraulics, spindles, tables/axes, idle, energy recovery), and alternate energy sources for operation (fuel cell, solar, etc.) and energy storage/recovery capability. In addition, the working envelope can be optimized with minimized environmental requirements and machine work envelope/machine footprint minimization. One can also consider design for re-use/re-manufacturing/component upgrade.

At the process microplan level we can consider feeds/speed for minimum energy roughing and finish machining, plans for minimum consumable use, efficient spindle/tooling design and optimized tool paths for high productivity and minimum energy. At the system level we can consider energy "load balancing" over line/system and over the entire production facility or plant, resource/consumable optimization over the line, and minimized environmental impact over line/system and plant.

Many controller, drive companies, and some machine tool companies, already are beginning to address the technology to make some of these "wedges" realizable.

4.2 Where do we start?

Energy (or, over time, power) use in manufacturing is very dependent upon characteristics of the machinery and processes. A number of studies have been done on the use of energy in machining, starting with Gutowski [7] and most recently with Diaz et al [8], [9]. The power consumption may be classified as: constant, variable, and processing power. Constant power consumption is due to auxiliary equipment that consumes power at a specified rate independent of material processing inputs – for example, the computer panel, lighting, and coolant. Variable power is consumed by machine tool components such as the spindle motor and the axis drives. Without considering the power to remove material in the cutting process in machining, the constant and variable power consumption together form the "tare" power consumption of the machine tool since this is the minimum power that will be consumed for a given set of process parameters regardless of whether or not material is cut.

When formulating strategies for reduction in machining energy consumption, one must consider whether or not the operation is „tare heavy" or „process heavy", Figure 5.

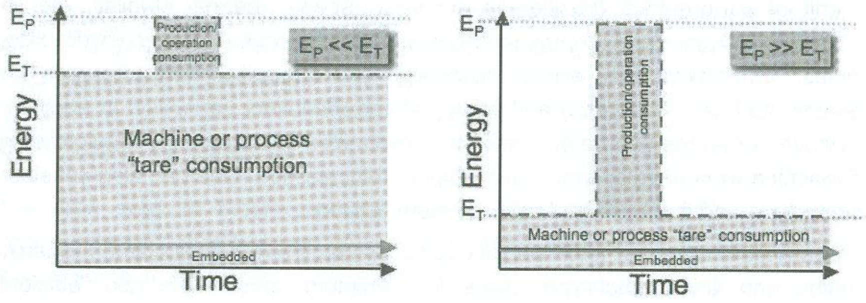

Figure 5: *Tare heavy, E_T, versus process heavy, E_P, energy consumption*

If the process energy is relatively small compared to the tare energy (as in micromachining at high spindle speeds), then the strategy will be to reduce the machine tare consumption. The inverse applies to process heavy energy consumption. Table 1 below details some potential strategies for various modes of operation depending on the regime of machining. Material removal rate, MRR, and machining cycle time, t_c, as well as cutting speed, v, and feedrate, f, are key variables.

Table 1: *Strategies for energy reduction*

Mode	$E_P << E_T$	$E_P \sim E_T$	$E_P >> E_T$
Operation (with process)	Highest MRR Shortest t_c	Highest MRR or Optimize process	Optimize process (tooling, path, f, v)
Operation (w/o process)	Idle/sleep or Reduce tare	Idle/sleep or Reduce tare	Reduce tare?
Embedded (no operation)	Reduce embedded energy: material, fabrication, transport & installation, maintenance, removal and recycle/remanf'g		

5 Applications

Application of green manufacturing research falls into three general categories: process technology and machine tools, metrics and analysis tools, and systems. We briefly review here some of the current research in these areas with apologies in advance to those whose work we are not able to mention.

In the area of process technology and machine tools work is on going on design of machine tools for reduced impact in [10], based on "light-weighting" machine components, determining baseline energy consumption and process related effects for optimizing energy consumption in machining in [8]. [9], [11], and [12]. Much of this research is the subject of the current CIRP Working Group on Energy and Resource Efficiency & Effectiveness (EREE) [13] and is published in the annual CIRP International Life Cycle Engineering Conference [14]. With respect to metrics and analysis tools, a good review of this work, and the tradeoffs associated with different objectives of the analysis and the „manufacturing space" on which the analysis is focussed, is found in [15]. A more detailed discussion of metrics for evaluating sustainable manufacturing, specially with respect to green house gas emissions, is found in [16].

Finally, under the broad category of systems, we look at the work on life cycle analysis (LCA) applied to manufacturing and, in specific, machines and machining. Although not LCA, life cycle costing is being expanded to include environmental effects [18]. The recent work on LCA for manufacturing is built on early work by Shimoda [19]. Work by Diaz et al [20] extends this to comparisons of two style milling machines operating in different production environments.

6 Summary

This paper has reviewed some of the basics of green manufacturing. The changes in products and processes due to energy awareness and environmental consciousness create many opportunities for sustainable technology development. The tools, metrics, process enhancements, analytical techniques, systems and business strategies that we develop will insure that manufacturing plays a significant role in creating a sustainable future. But, there is one important aspect of the discussion we've not touched upon, the social aspects of sustainabiity, and this remains a subject of intense interest and importance for future research and it will benefit from our input.

7 Acknowledgements

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