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Moving Towards Green and Sustainable Manufacturing

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The pressing needs of energy, water and other resource conservation worldwide is a major engineering challenge. In manufacturing, developing green technologies (from process and tooling to the entire enterprise) is one way to insure that future manufacturing systems are sustainable. To do this, innovation in advanced manufacturing is needed. The basic requirements of green technology are discussed along with methods and tools to insure they are effectively applied and their impacts measured. For situations in which the manufacturing environmental burden is less than the burden for the use of the product leveraging is proposed to insure a total life cycle impact reduction. Examples of several green technologies are presented.

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1. Introduction

The world is moving towards implementing green manufacturing in an effort to achieve sustainable manufacturing. Companies are realizing that sustainability is an attractive strategy for both business practice (saving energy and other resources, responding to government regulations, reducing supply chain risk and uncertainty) but also to respond to consumer demands and maintain competitiveness. When one realizes that all future energy, transport, medical/health, life style, dwelling, defense and food/water supply systems will be based on increasingly precise elements and components, then manufacturing for an energy and environmentally aware consumer, manufacturing alternate energy supply systems, and providing machine tools and other production equipment that uses less energy, materials, and space for efficient factory operation is a competitive advantage. In fact, it drives innovation in manufacturing.

At a higher level, this movement needs to address social responsibility (specially the social dimension of sustainability) in the context of this shift toward sustainable manufacturing. To do this, and the more focused task of implementing greener production technology, it is necessary to develop the tools and methodologies so that engineers and manufacturers can institutionalize socially responsible decision-making practices for design and manufacturing.

One key consideration is the effective utilization of resources and increasing resource productivity as a driver for manufacturing (including green manufacturing) innovation. There are a number of ways to improve resource effectiveness including:

1) Avoid use of a resource in the first place
2) Light-weighting
3) Increased yield
4) Reduced footprint of resources
5) Insure high re-use yield and low "cost" of reuse
6) Leveraged resources
7) Extended life

All of these have implications for manufacturing or can be considered as resulting from improvements in material conversion, manufacturing processes and product design for manufacturing.

This paper reviews background for assessing the impact from consumption and where manufacturing fits in, then some ideas about resource productivity (improving product value with reduced environmental impact) and, finally, discusses the role of green and sustainable manufacturing technology with examples as a strategy for achieving sustainable production.

2. What Is the Impact of Manufacturing and What Can We Do About It?

2.1 IPAT Equation

There are a number of methods to estimate the impact of technology (and the role of manufacturing) on the environment. One of these is referred to as the impact equation or IPAT for the three principal components of it: population (P), affluence (A, measured by GDP/person) and technology (T, measured as impact per unit of GDP) where

GDP is gross domestic product. The product of P *x* A *x* T is, according to some, a measure of the impact of the technology as well as the growing demands of population wanting to live better. The equation is attributed to Ehrlich and Holdren.[1] Since we can do little about population growth, and it is not reasonable in general to assume we can discourage people from wanting more affluence, then the role of engineers and technologists is to decrease the impact of a product, for example, while still providing the same or more value to the customer. That is, more effective use of technology to deliver value.

How much more must we improve this "effectiveness"? It turns out – a lot. At present our impacts are too large. According to Hutchins,[2] we are utilizing 1.5 times the capacity of the planet in terms of resource consumption with an impact of emissions of CO_2 and pollutants, depletion of resources, solid waste, etc. Looking to the future Hutchins estimates that population (the P in IPAT) will increase by ~40-30% by 2050. Affluence, A in IPAT, is also growing quickly in many nations – ~3-5x increase by 2050. And this is to be expected. Everyone wants a better standard of living. The result is that we may need to increase our efficiency (that is, reduce the T) by a factor of nearly 10! Meaning, we've got to reduce impact of our products while maintaining their value - or growing it - in the eyes of the consumer.

2.2 Resource Effectiveness or Productivity

We are usually acquainted with the term "labor productivity" It is defined as the relationship of "output to the labor hours used in the production of that output" in the context of manufacturing. It is a closely watched term and, usually thanks to automation, has been increasing in industrialized countries. To address the need to improvement in technology and hence reduce impact per unit of GDP it is proposed to look closer at resource productivity.

Following on the definition of labor productivity, resource productivity would be the amount of output (value) created per unit of resource expended (or unit of impact). This might be measured in the traditional units of resource (or impact) such as: Global warming gases emission (CO_2, methane CH_4, N_2O, CFC's), process material yield or % recyclability of the product, % reuse of materials or remanufacturing, as well as pollution (air, water, land). These could be recorded on a per capita basis, or per GDP, per area/nation, and so on. As with higher labor productivity which bolsters a nation's labor-cost advantage, higher resource productivity maintains a strong resource-cost advantage.

A number of examples of ways to improve resource productivity come to mind. There are three basic strategies to greening manufacturing (use clean energy sources, improve manufacturing technology, use lower impact materials,[3]). If one looks at the manufacture of an automobile, then, the amount of energy that is consumed in the production process is basically fixed for a certain vehicle – but the impact of that is not! If the vehicle is manufactured where the energy mix is heavy on renewables, the impact of manufacturing will be less than if it is manufactured where the energy mix is heavy on fossil fuels. Using the same technology thus yields dramatically different impact results depending on production.

Similarly, one might consider the utilization of materials – process yield. Allwood[4] addresses this and gives several examples in which the "cumulative yield" (meaning the amount of material from the raw stock - in this case liquid metal in the ladle after it was refined - to the finished product) is contrasted with the "cumulative process energy" representing the cumulative increase in energy per unit mass required to get the material to the various stages along its path to a product. In the case of both steel and aluminum the cumulative yield was as low as 40-50% in the case of some products (like beverage cans) and, for some aerospace components fabricated of aluminum, in the low 'teens. And the "cumulative impact" of that material when it finally got into a product necessarily included the energy that processed the "wasted" material along the path to production. Just because the material that is left on the shop floor is recycled does not mean the embedded energy, or its environmental impact, in the product is recovered. Increasing the yield, by improved process technology, can drive reduced impact for the same value of the product.

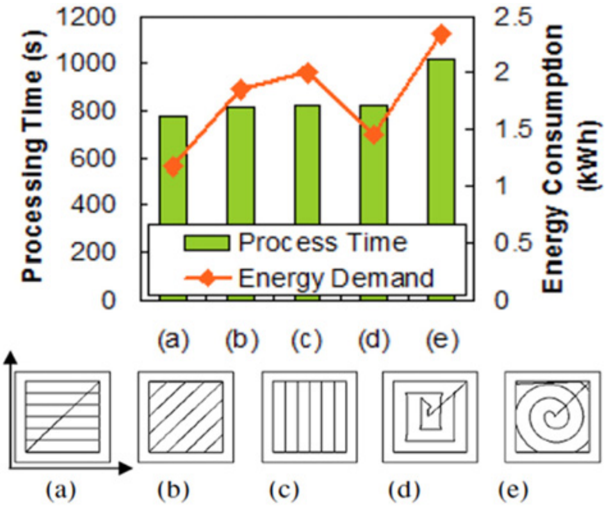

Fig. 1 Processing time and energy consumption of various tool-paths for creating the same feature[5]

3. Improving the Process

3.1 Process Effectiveness

There are improvements at the process level that can reduce energy, material and other resource consumption. For example, at the tool path planning level, given the specific operating characteristics of most modern computer numerically controlled (CNC) machine tools including construction (with stacked axes) and controller performance, there is usually a preferred orientation of a workpiece on the machine tool and, for that orientation, a preferred tool path to remove the desired material.[5] This can often result in substantial savings in energy to produce the same part feature with no loss of cycle time (Fig. 1).

Further, at the micro-planning level (meaning feeds, speeds and resulting material removal rates, MRR) specific energy of material removal (J/cm^3) is inversely proportional to MRR. This implies that higher removal rates will be more efficient if other process conditions allow.[6] A summary of strategies to lower the machine tool's power demand is shown in Fig. 2 from.[9]

3.2 Idle vs Production Consumption

For most advanced manufacturing technologies, for example CNC machines, the power consumption during the non-operation or idle state is almost as much as in production – especially at small workloads, as

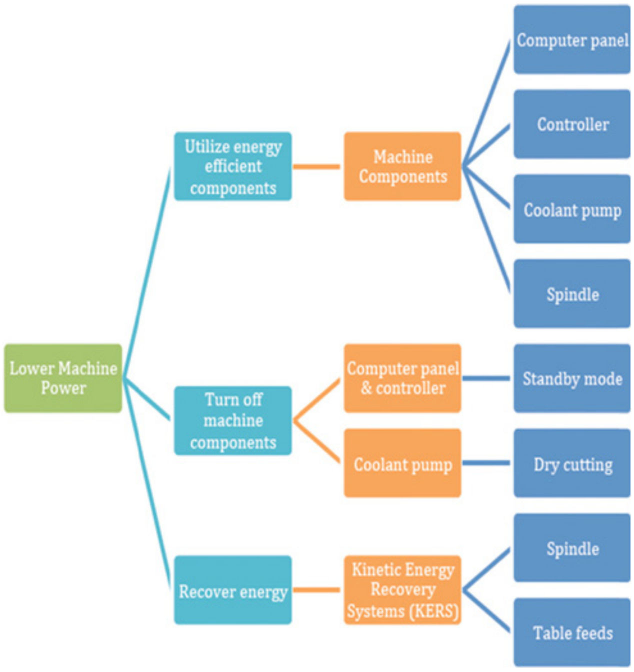

Fig. 2 Summary of strategies to lower the machine tool's power demand[9]

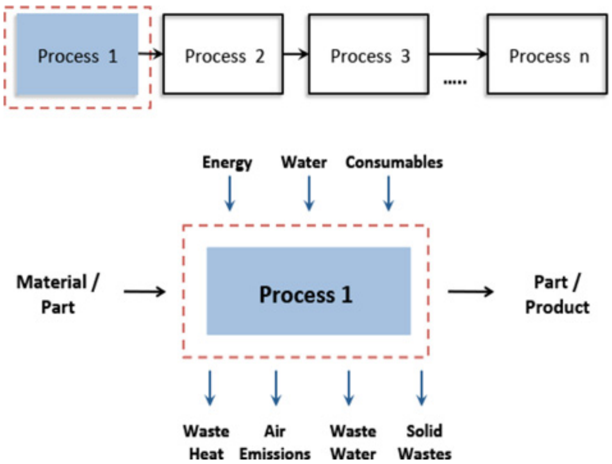

Fig. 3 Process chain analysis and resource consumption[10]

with machining chip load.[7] Others have shown impressive improvements in reducing the idle phase energy consumption.[8] This, then, leads to planning the flow of parts through the set of machines in such a way as to balance the need to availability of the machines to keep production levels smooth with the desire to avoid lots of idle time and the incumbent waste of energy. Research reported in[9] indicates that by careful planning, the utilization of a group of machine tools can be optimized to insure that both the idle time is minimized (reducing unproductive energy use) and productive flow of parts through the system can be assured with accompanying energy efficiency.

4. Improving the System

4.1 Process Chain Analysis

Most manufacturing is done with a series of machines linked together in a process chain. The resources used by the chain are the summation of the individual process consumption. In addition, interactions between process chains must be determined (e.g. a prior step with better process control can reduce the need for a following process). Fig. 3, from,[10] illustrates the systems approach. For each process consumption, as well as production, details are tracked such as energy use (kWh), water use (l), consumables (m^3, kg, m), waste generated (kg), and air emissions (g). These consumption data can be converted into cost and impact as global warming potential (CO_{2eq}), energy cost, water cost, etc.

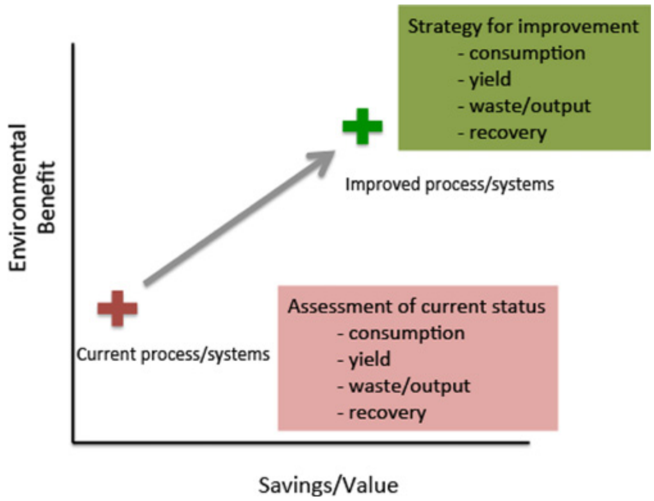

Fig. 4 Eco-route map concept for assuring reduced impact/value in manufacturing process planning[10]

4.2 Eco-Route Maps

In decision making for both reducing environmental impact as well as insuring manufacturing productivity, quality and cost targets are met (or exceeded) both environmental and cost constraints must be considered. If we are to insure that the value is increased at lower impact then this is critical. One solution is to develop what might be called "eco-route maps" – similar to those one might prepare before taking a road trip. These maps show, from a current baseline of cost or value and environmental impact, a desired trajectory for future process, system, facility or enterprise improvement (Fig. 4 from[10]).

A combination of the detailed process and process chain consumption and performance data with the data on energy and other consumable use, and its corresponding impacts, can then be evaluated on the eco-route map to insure that the improvement, along both dimensions, is positive and substantial.

5. Leveraging - Manufacturing vs Use Phase Impacts

As important as manufacturing is in reaching sustainable consumption, there are circumstances for which the contribution of manufacturing to the life cycle impact of a product is small – maybe measurably small. This is usual for use phase impact dominant (compared to manufacturing phase) products - automobiles and other transport means for example. So what is the role of manufacturing here? The concept of leveraging, meaning improved manufacturing of the product to substantially impact the performance of the product, comes into play here.

Improvements in internal combustion engines, primarily due to improved manufacturing processes (for example, reduced friction due to enhanced tolerances or surface finish, precision casting, fuel injectors with

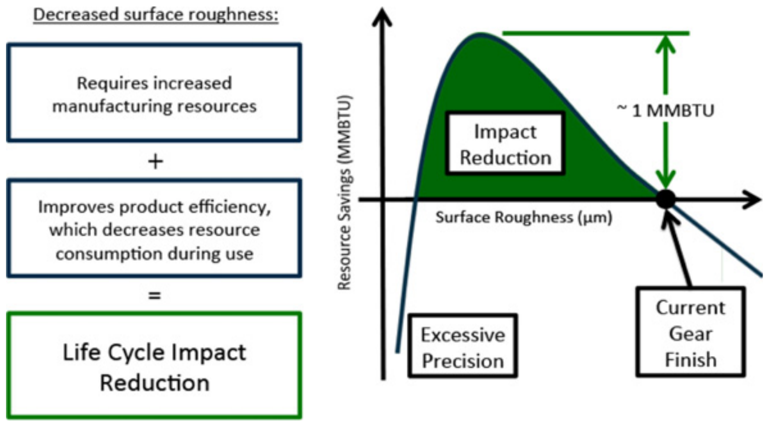

Fig. 5 Leveraging manufacturing precision for better life cycle product performance – automotive gear train efficiency[12]

optimized nozzles, or light weighting due to enhanced material joining and forming) have yielded dramatic improvements in fuel efficiency of these engines. In this sense, an increase in the manufacturing process capability (usually at the expense of small additional energy or processing) yields a tremendous (compared to the investment of energy) savings over the life of the vehicle in all categories – green house gas reduction, water, air pollution, etc. Fig. 5 illustrates this for reduced surface roughness in automotive gearing systems. The potential life cycle improvement can be huge.

6. Conclusions

Manufacturing can play a significant role in reducing the environmental impact while increasing the value of products – contributing to sustainability. The process, machine, system, factory and enterprise are all part of this. The tools and analyses reviewed here offer a systematic approach to this and offer opportunity for the design and manufacture of truly sustainable products.

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