Leveraging Manufacturing for a Sustainable Future

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Abstract
Manufacturing offers many opportunities for reducing environmental impact, utilizing resources more efficiently and, overall, greening the technology of production. These opportunities are most often related to process, machine or system improvements that impact only the operation of the process, machine or system. But, there is more potential in manufacturing enhancements to have a larger impact on the life cycle impact of the product the manufactured item is used in. This is referred to as "leveraging" and several examples of this are given, along with definitions of the fundamental terms. The potential for leveraging in manufacturing to have an impact on sustainable manufacturing and some future requirements are described.

Keywords:
Process; Machine; System Improvement; Life Cycle Impact; Make versus Use

1 INTRODUCTION

Manufacturing offers many opportunities for reducing environmental impact, utilizing resources more efficiently and, overall, greening the technology of production. These opportunities are most often related to process, machine or system improvements that impact only the operation of the process, machine or system. But, there is more potential in manufacturing enhancements to have a larger impact on the life cycle impact of the product the manufactured item is used in. This is referred to as "leveraging" and identifies manufacturing-based efficiencies in the product that are due to improved manufacturing capability but which, in the long run, have their biggest effects on the lifetime consumption of energy or other resources or environmental impacts.

First, what is meant by the term "leveraging"? We understand a lever to be a device to increase mechanical advantage, as a bar used with a fulcrum to pry a heavy load allowing a larger load to be moved than with simple force alone. Leveraging is used as a transitive verb, usually in financial discussions such as [1]:

> *"The use of credit or borrowed funds to improve one's speculative capacity and increase the rate of return from an investment."*

The general idea is to employ resources in such a way as to insure a larger return on the effort (or in financial terms, money) than might otherwise be realized.

How does this relate to manufacturing? And, in specific green manufacturing? This will depend on the component being manufactured by a machine or process and its eventual use in a product.

This paper will first provide some definitions so that the use of terms like green manufacturing, sustainable manufacturing, etc. will be understood. Then, the concept of leveraging manufacturing will be explained and several examples of will be given of situations that provide leveraging along with some that do not. Finally, future directions in sustainable manufacturing driven by leveraging are suggested.

2 BACKGROUND AND TERMINOLOGY

2.1 Green and sustainable

The familiar 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" [2] does not really speak to manufacturing but makes the key point that we need to at least "do no harm." The US Department of Commerce defines sustainable manufacturing 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" [3]. We define green manufacturing here as a first step towards sustainability.

These first steps were proposed as green manufacturing "technology wedges" in [4] after a concept proposed by Pacala and Socolow [5] 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. They argued that, rather than trying to find one solution to correct this increasing mismatch between what is required and what is being done, we should concentrate on "technology wedges" – small advances and improvements that, when added up, have the effect of a large change.

These wedges make a lot of 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

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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, from [6]. 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.

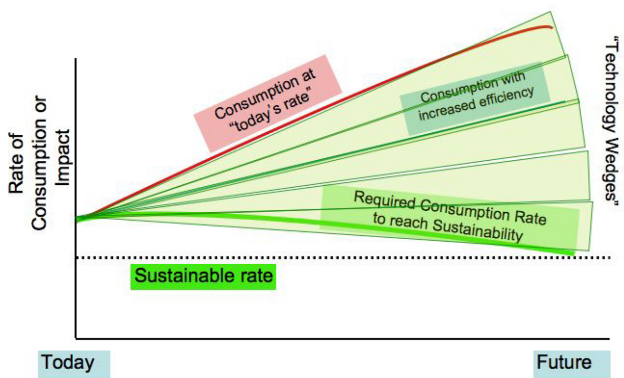

Figure 1: Illustration of sustainable consumption and technology wedges, [6].

It is our role of manufacturing researchers to develop the wedge technologies. Individual wedges might be considered as "green" manufacturing steps. If there are sufficient greening steps we can achieve sustainable manufacturing.

2.2 Tracking progress

To insure that real progress is being made it is necessary to define metrics to measure change. Recall the "master equation" for impact attributed to John Holdren and Paul Ehrich [7]. This equation, sometimes referred to as IPAT, defines human impact (I) on the environment as the product of population (P), affluence (A, measured as GDP/capita), and technology (T, measured as impact per unit of GDP). Manufacturing has its impact on the T part of the equation – the impact per unit of technology. This is the impact per GDP of manufactured products. By reducing that impact, we start to "bend the curve" of the consumption or impact curve seen in Figure 1.

The challenge is to come up with technology wedges that will reduce the T part of the équation at a rate sufficiently fast to offset population growth while at the same time make a dent in the impact that is already too high.

Metrics are used by engineers for analyzing information and data to enable better decision making, including trade-offs among several alternatives, and for design. 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

To be able to understand the effect of the improvement or change being measured, 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)

Then, a measure of the change in the T term of the impact équation can be determined.

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 business operation including business travel, shipping of goods, resource extraction and product disposal).

2.3 Leveraging

We can define two different classes of leveraging of manufacturing. The difference is due to the magnitude of the impact. That is, whether it impacts only the performance of the manufacturing process, machine or system or whether it impacts the performance of the product resulting from the application of the process, machine or system. An additional distinction must be made for products used in manufacturing – for example, machine tools.

In the case of an improvement, say in energy consumption of a process, we would require that, at minimum, the "cost" of the improvement (in embedded energy, carbon footprint, etc.) would be more than offset but the reduction in energy consumption or carbon footprint in operation of the "improved" process. This is the basic definition of energy payback or green house gas return on investment. The magnitude of the impact reduction can be measured simply by knowing the number of manufactured products coming from the process over the life time of the process. This is a minimum amount of leveraging for any contemplated process improvement to insure that we are making progress.

A second, more impressive, leveraging is due to process (or machine or system) improvements that have an inordinately high ability to reduce the impact of the product of the manufacturing operation (or machine or system) over the lifetime of the product use. The original process improvement may not have been made as part of a greening analysis of the process but is due to the introduction of new technology, machine capability or materials. It is this second type of leveraging that is likely to have the greatest potential for reducing the T term in the impact equation – making a larger than normal reduction in the product impact/GDP during the product's life time.

Why this distinction is important is discussed in the next section.

3 WHY LEVERAGING IS IMPORTANT

3.1 Does manufacturing matter?

The base of this discussion is an assessment of whether or not manufacturing is a significant component of energy and resource consumption and the impact from this consumption, and, then, whether or not changes in manufacturing can really help overall. A review of all the data, pie charts and discussions about how much of the world's energy use is attributed to manufacturing is not presented here.

Allwood et al [8] point out that industrial carbon emissions are predominately due to production of goods in steel, cement, plastic, paper, and aluminum. With the demand for these materials expected to double at least by 2050, during which the global carbon emissions are desired to be reduced by at least 50%, simply improving process efficiency will fall far short. Allwood suggests several strategies for industrial emissions reduction in addition to process efficiency, increased recycling, and carbon sequestration and storage, as: (1) reducing demand for materials; (2) nondestructive recycling; and (3) radical process innovations which allow shorter, less energy intensive process routes to yield the completed component. These all address the T term in the IPAT equation.

But, for "general product manufacturing" is there enough that can be accomplished by manufacturing improvement? Specially if we apply this to what many of use consider our core process capabilities – like machining?

3.2 Automobile manufacturing example

If we think about where the major energy consumption associated with a product occurs we can divide the space up into two regions – manufacturing and use. We see that "things that don't move or need power to operate" like bridges, furniture, etc. are dominantly manufacturing phase consumers of resources and, by extension, impact. Things that do "move and need power to operate" like automobiles, airplanes, buildings, etc. are use phase heavy. Interesting to note are the items that are close to the break-even (imagine a 45 degree line on a plot of use vs manufacturing impact graph for products).

So, what about automobiles? At a presentation at the ICMC Conference in Chemnitz in September 2010 by a representative of the automaker VW, the speaker mentioned that, by their analysis, about 20% of the impact of a typical VW Golf A4 car came from manufacturing while 80% was due to the use phase. One can find data on the GolfA3 (marketed from 1991-1999, also called the Polo) from some time ago and the comparison was similar. Figure 2, from [9], shows the energy consumption during the manufacturing phase of the GolfA3 in Gj/auto.

Materials and part suppliers account for much of the embedded energy in the manufacturing phase. Machined components, such as the gear box and engine are a small percentage of the total (accounting for about 10% overall or about 25% with materials and parts from suppliers included).

If one looks at the impact of the auto, including car production, fuel production and use phase, Figure 3 from [9], it is clear that the fuel production and consumption in the use phase dominates all categories of emissions to air and water with the exception of dust generated by material production and casting of some components and painting of the vehicle and biological oxygen demand impacts on water.

Looking a bit closer at the data above, does this make sense in terms of reducing the impact/GDP? If we focus only on the manufacturing phase we may not be encouraged - specially if the predominant impact is in the use phase.

Consider the VW Golf example of 20% manufacturing phase impact versus 80% use phase impact. If we think about the areas many in our community work in a lot, machining, and we assume about 20% of the manufacturing is machining or machining related, that gives us a potential for improvement of 20% of 20% or only 4% (and then only if we get rid of all machining!). Let's assume that some of the better technology for improving machining efficiency is employed, say some specialty tooling material that reduces machining power consumption, and that is worth another 20%. Now we are down to .8% (20% of 4%).

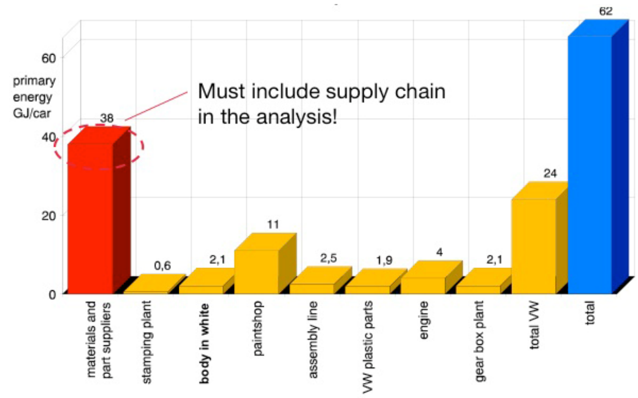

Figure 2: Primary energy consumption for VW Golf manufacture [9].

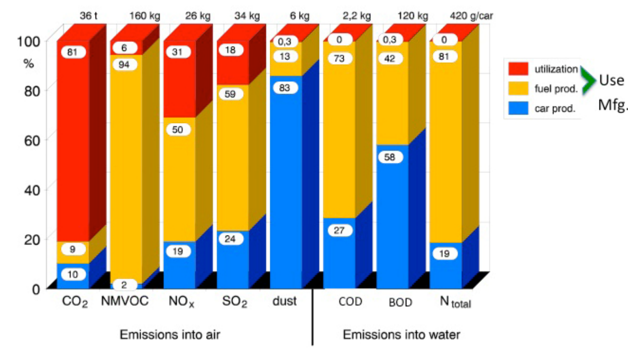

Figure 3: Use vs manufacturing phase impacts for VW Golf [9].

One could argue that this is hardly worth the effort it would seem. Of course, if you are paying the electricity bill for the factory and this 8% technology wedge is added to a lot of others in machine operation it can add up to real savings. But, still not impressive compared to use phase impacts. That is, impact over the full life cycle of the auto.

More recent data from Volkswagen for the Golf A4 indicates that some improvements have been made (for example reduction of primary energy used in production, use and end of life due primarily to improved fuel consumption (a 20% improvement from 8.1 liter of fuel/100 km to 6.5 l/100 km for the gasoline engine) [10].

3.3 Accounting for more of manufacturing's impact

The question is, then, what is the true leverage effect of manufacturing on the life cycle impact of a consumer product – one that has its dominant impact in the use phase rather than the manufacturing phase? If we are speaking of a manufacturing machinery builder, like a machine tool company, then we can argue that the machine tool has its largest impact in the use phase so that improvements in energy efficiency of the machine will been seen over its life [11] since it is the "product."

The thesis here is simple. If improvements in manufacturing yield a substantial reduction in the life cycle impact of a product, should not manufacturing get some of the "credit" for this improvement. And, by similar reasoning, can we claim this as a part of "green manufacturing" contribution towards sustainability since it is a major element in reducing the technology impact of the product – the T term in the IPAT equation?

The next section gives some examples of this leveraging effect.

4 EXAMPLES OF LEVERAGING

4.1 Basic influences

Manufacturing has a number of fundamental effects on a product. In no particular order, manufacturing can:

- guarantee a certain level of precision or accuracy of the produced component
- allow the use of advanced materials (enhance strength to weight, improved surfaces, wear resistance, thermal stability, etc.)
- allow reductions in process steps or sequences
- combine processes for enhanced effects as in hybrid processes or mill-turn machine tools
- achieve complex shapes or features to improve performance
- and so on

There are more but you can get the idea.

How these manufacturing induced effects influence the life-cycle performance of the product must be clearly understood to explain the full potential of leveraging. This influence usually comes from the extension of one of the above listed effects onto the energy consumption or “environmental performance” of the product the manufactured components are used in.

A simple example might be a spindle motor for a machine tool. If the production technique for the motor, using advanced magnetic materials, allows the construction of a motor that extracts more useful work from the energy supplied to it, then the manufacturing effect is leveraged over the life of the spindle.

Alternatively, if the improvement in energy consumption is due to controller related performance enhancement, as the 40% reduction in energy consumption illustrated by Mori Seiki due to overall system component improvements and optimum acceleration of spindle and servo motor during machining [12], this is not due to manufacturing leveraging but, certainly, improves the life cycle impact of the machine tool – the product in this case.

4.2 Leveraging examples

Two examples are presented here that illustrate the concept of leveraging manufacturing with life cycle impacts on the product that the manufactured component(s) is (are) used in. And the life cycle impact is substantial and most of the benefits are due to manufacturing.

Both of these examples relate to improved machining tolerances and their impact on product performance. On an aircraft airframe (a large one like a B747 or the A380) savings in weight correspond directly to savings in fuel. And many other aspects of an aircraft scale with weight. This is, to some extent, true also for an automobile. That is the second example

If the machining process for large airframe components is under control and precision manufacturing principles applied, a reduction in machining tolerances from approximately +/- 150 microns to +/- 100 microns on the features of the airframe can account for a weight reduction of 4500 kg/aircraft and substantial fuel savings (8%) [13]. This allows an increase of 10% in passenger load (the engines don't need to carry as much plane), or increase in cargo payload and a substantial reduction in manufacturing cost of the aircraft (less material and improved assembly) and the accompanying reduction in scrap. And less fuel consumption means reduced CO_2 impact from aircraft operation. The accumulated savings over the life of the aircraft are incredible. The fuel consumption per km is estimated as 11.88 L/km (or about 5 gallon per mile). Thus, the CO_2 emission rate can be estimated at 30.64 kg/km [14]. A reduction in fuel consumption of 8% results in a reduction of almost 2.5 kg/km CO_2. And this is over the life of the aircraft – many millions of kilometers.

The next example relates to a similar impact on product use for an automobile. It is also due to enhancement in manufacturing capability due to precision manufacturing.

The improvement for the Boeing aircraft example was based on tightened tolerances allowing increased structural performance by better control on dimensions - resulting in lower weight components. Looking at improvements in engine performance for automobiles we can see similar improvements. The performance (power density in kW/l) of diesel passenger car engines is shown in the graph in Figure 4 from [15]. With better tolerances, better

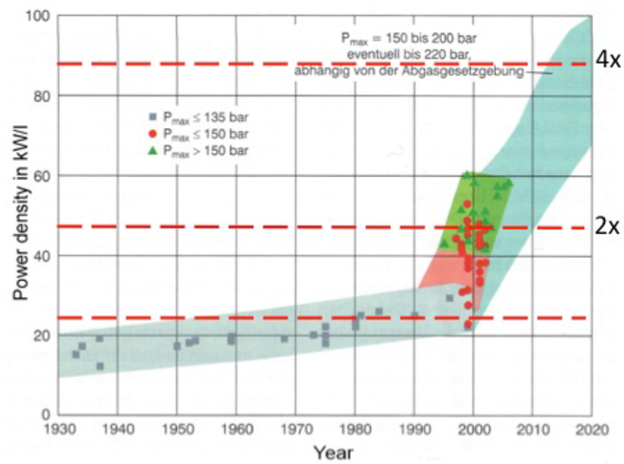

Figure 4: Change in power density over time for Diesel engines [15].

surface finishes, better control of orifice size and shape on the fuel injector nozzles (with diameters on the order of 60 microns), tighter control on cooling channels and fluid flow in the engine due to enhanced casting techniques, and so forth, the engine (still working on the same old Diesel principles) performs dramatically better.

The "dog leg" in the chart above corresponds to the introduction of high performance, precision, manufacturing to the power train manufacturing in the automobile. In the years since 2000, the power density has been improved by double (in 2007) and anticipated to quadruple by 2020, Similar improvements can be seen in the transmission as well. And, with advanced sheet metai forming technologies (another manufacturing technology enhancement) and replacement of metal components with non-metallics (manufacturing and materials enhancement) more improvements would be anticipated. This is not to suggest that precision technologies had not been employed before. But, the engine and associated fuel injectors, etc. were designed to take advantage of increasing manufacturing performance and, as a result, yielded tremendous product performance as well.

And that is how to reduce the technology impact per GDP. Manufacturing dramatically increased the efficiency of fuel utilization in the internal combustion engine.

The small percentage of manufacturing phase improvement has a giant leverage effect on use phase impact. Since the principal element in use phase impact of the automobile, the reduction in consumption (due to increased power density of the engine), hits both the fuel production impact as well as the fuel consumption impact there is additional impact. In the Golf A3 data for emissions, Figure 3, 90% of the CO_2 impact was due to the use phase (81% from driving and 9 % from fuel production). A doubling of the fuel economy, by manufacturing induced engine efficiency improvements, by precision machining and processing will essentially halve that (same distance driven) - or account for, in the case of the Golf A3, a reduction of some 16 tons of CO_2. And if, in the process of manufacturing enhancement, we save most of our 4% impact from machining, that's .4 ton of CO_2. So, for our .4 ton we get a return of 16 tons (a factor of 40!).

4.3 The fine print

There are constraints of course. The technology enhancement (the "wedge") needed to improve precision of the machine tool to enable some of the product performance increases may not be strictly "green" (meaning there is a cost in terms of embedded energy, energy/unit product, or other measure). Trends in machine and process design are showing that one can enhance the performance of the manufacturing process and also realize reduced impacts. Recall the Mori Seiki example cited earlier. But, this needs to be carefully accounted for.

A second issue is whether or not manufacturing can rightfully claim credit for any or all of these improvements under leveraging. Traditional design textbooks outline the design process in stages with clever designs being turned into real products through manufacturing. So, for sure, the role of manufacturing as a design enabler is undisputed. In that case, we can claim the benefits of leveraging manufacturing as well.

5 SUMMARY

This paper has proposed a view of the potential for manufacturing to play a more significant role in reducing the environmental impact of technology. The manufacturing capabilities that yield aircraft or automobile engines with dramatically reduced fuel consumption, or structural components for aircraft that allow higher payloads per unit of aircraft structure, or advanced processes that yield lower power electronics for reduced energy consumption, and so on, are examples of leveraging manufacturing.

We cannot claim all benefits in product performance stem from manufacturing. An enhanced wash cycle on a home laundry that reduces water and energy consumption has likely very little to do with manufacturing technology improvements. But we should stand up for those manufacturing driven improvements that, on their own, are responsible for substantial environmental impact reductions.

The challenge raised by researchers, like Allwood, pointing out the fundamental changes needed in production technologies (specially for materials processing and efficient material use) must be complimented by the tremendous potential for leveraged manufacturing. It points out, at least, the significant role that manufacturing (broadly defined and over all processes and systems) can play in creating a sustainable future.

Finally, we need some numbers! The arguments presented here are based substantially on empirical observations. A more careful analysis of the tradeoffs of competing technologies with respect to potential leveraging effects must be done for several case studies. That is on the agenda for our future work.

6 ACKNOWLEDGMENTS

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