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SUSTAINABLE MANUFACTURING: FROM CAR PARTS TO NANOBUMPS AND ECOSYSTEMS

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Abstract: *Sustainable manufacturing is gaining more and more interest from companies and researchers. In this talk, we will show how such a systems view is needed to identify the correct focal areas. We will use examples from automotive engineering where we quantified environmental loadings to demonstrate where new research and development should take place to achieve higher reductions in environmental impact. We will also present ongoing work in biologically inspired design aimed at identifying recurring principles in Nature that could provide fundamentally new engineering design principles for achieving sustainable designs. For example, one can apply the Lotus effect to reduce fouling of products through creation of self-cleaning surfaces. As will be shown, care must be taken though to balance claimed benefits in the use phase with upstream production impacts. At a higher level, closed loop production networks can also be developed using ecological principles. From Lotus effect to closed loop supply chain integration, sustainable manufacturing must include a systems view crossing multiple scales in order to have true sustainable benefits.*

1 INTRODUCTION

Companies are becoming more and more concerned with the environmental impact of their products and processes because a growing number of people, including consumers, are realizing that there is an associated cost to society. All products and processes affect in some way our environment during their life-span.

"*Sustainable Development*," that is "development that meets the needs of the present generation without compromising the needs of future generations" (UN 'Brundtland' Commission, 1987) is seen by many as the ultimate goal, but the challenge is how to get there. In this paper, we highlight some important elements that need to be part of both a research agenda as well as corporate strategy to move from the current situation to sustainable development. When dealing with sustainability issues, one always needs to be aware of unintended consequences that can happen at multiple levels. Hence, we emphasize the need for a systems approach to addressing sustainability.

2 SYSTEMS VIEW

Many are looking for a technology that will solve our environmental problem. In 2001, the National Science Foundation and Department of Energy sponsored a comprehensive global study on Environmentally Benign Manufacturing, which is defined by NSF as "a system of goals, metrics, technologies, and business practices that address the long term dilemma for product realization: how to achieve economic growth while protecting the environment?". The study found that there was no evidence that the environmental problems from our production systems are solvable by a "silver bullet" technology [1, 2]. Rather, the need for systems-based solutions was noted, requiring a comprehensive systems approach in which, e.g., the product's design is performed in conjunction with its logistical and recycling systems, integrating key disciplines such as environmental science and policy, engineering, economics, and management. Clearly, this raises the level of design complexity, and a need exists for a framework for such a systems-based approach that is both efficient and effective in reducing environmental impact while maintaining or increasing a product's technical and financial performance. An overarching question is how to achieve systems based approaches to sustainable design and manufacturing. While there are many researchers working to address important needs in sustainable manufacturing, the cumulative impact of the work is limited by its fragmented nature, lack of a systems view, and lack of connectivity to industry.

To highlight the importance of a systems view, consider Figure 1 where a schematic representation of a product's life-cycle is given. All parts and products start their life as materials that are extracted from the Earth. From these materials, parts are made that are sourced into subassemblies and products in production facilities. Products are shipped using a variety of modes through logistics channels to consumers and users. This is where traditionally the viewpoint of industry and engineering draws its boundaries. These products, production facilities, transportation modes, etc. are, however, part of larger urban and societal systems and this interaction can often not be ignored. The automobile is a good example. It is a privately owned product that is, however, dependent on a publicly owned road infrastructure. Similarly, companies have been depending on publicly funded landfills for their wastes. The industrial and societal system operates in connection to larger ecosystems, which in itself are bounded by the Earth's carrying capacity. As illustrated, this entire system obtains its power from the Sun, Moon, and Earth. Fossil fuels are basically ancient biomass that has been compressed into solid (e.g., coal) or liquid (petroleum) form over time.

The emergence of product take-back directives in Europe and Japan to drive hazardous products and material from landfills has forced manufacturers to include product recovery, recycling and reuse considerations in their designs [4, 5]. Given the plethora of options and processes, we have coined the term "re-X" to capture the various options that can be part of product take-back initiatives. Similarly, the term "demanufacture" is often used to characterize the process opposite to manufacturing necessary for recycling materials and products.

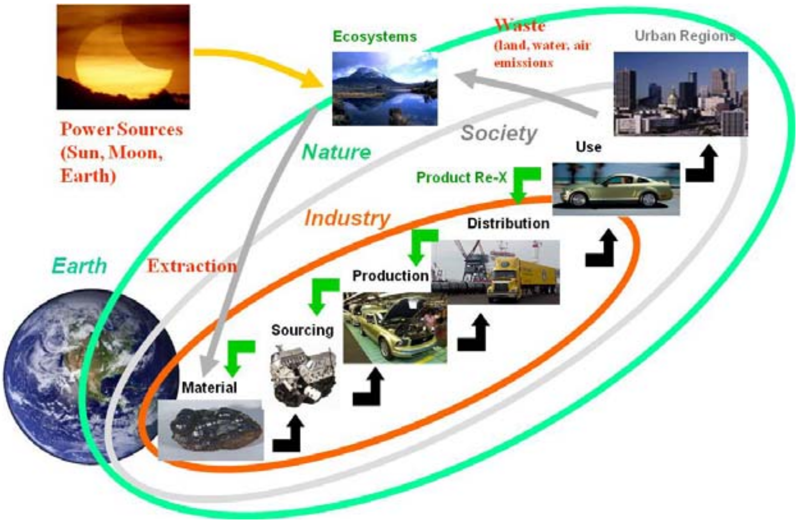


Figure 1: Multi-scalar Representation of Sustainability [3]

There are some key elements that are needed to move from our current "take-make-waste" production system to a sustainable system. Critical elements needed to achieve a systems view and solution to sustainability are life-cycle thinking, closed loop thinking, multi-scale/multi-level modeling, and understanding user behavior. In the following sections, we will highlight some of these issues.

3 AUTOMOTIVE PART EXAMPLE

To highlight why a life-cycle perspective is important, consider the example of a relatively simple part in an automotive powertrain, namely, an aluminum transfer casing as shown in Figure 2. In Figure 3, the energy consumption of individual processes in this part's life-cycle are given (excluding transportation, which has minimal impact). As can be seen in Figure 3, traditional manufacturing processes like machining have a very small impact compared to the production of the material. Figure 4 shows a similar trend for steel in context of the life cycle of a steel transmission gear. Data from the Energy Information Administration supports this. Primary metals and chemical production dominate in comparison to other manufacturing sectors [6].

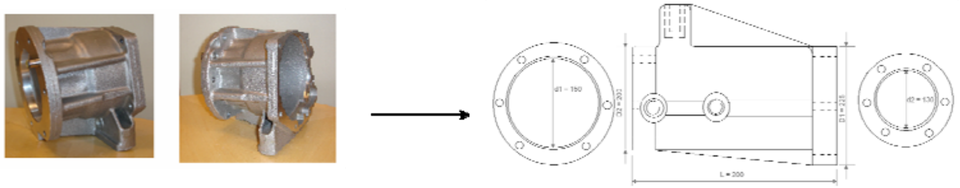


Figure 2: Automotive Transfer Case Picture and Drawing

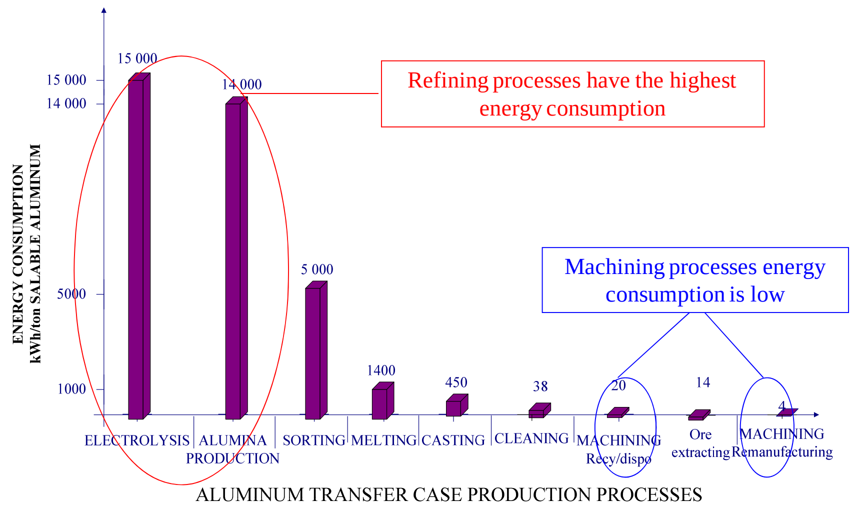


Figure 3: Transfer Case Energy Consumption [kWh/ton] [7]

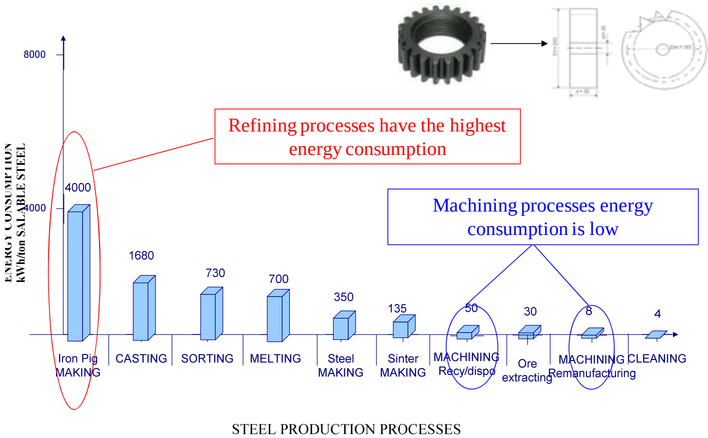


Figure 4: Steel Gear Energy Consumption [kWh/ton] [7]

This, however, is only the energy perspective and although energy is a key indicator for environmental impact, it is not the only measure. One should always consider different perspectives. For example, if one looks at water consumption for these products, one gets a slightly different picture, as illustrated in Figure 5. Although metal refining is again the dominant process, cleaning and machining have risen in importance. Although remanufacturing is often touted as a superior process in terms of energy savings compared to virgin product manufacturing, one has to pay special consideration to cleaning processes because they may cause unwanted environmental impacts [8, 9].

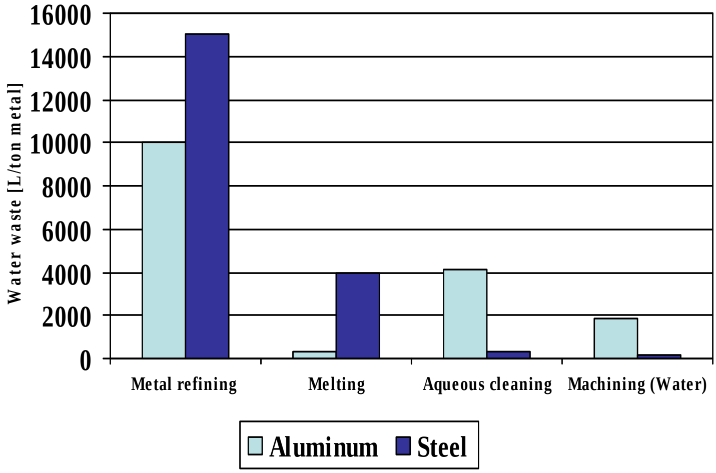


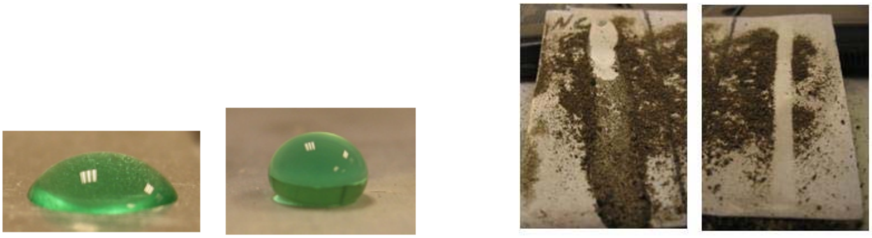
Figure 5: Water Consumption in Life-Cycle Processes [liters/ton] [7]

4 CHANGING THE PARADIGM – BIOLOGICALLY INSPIRED DESIGN

Given an assessment of impacts, the next challenge is to find an improvement consisting of a truly sustainable technology that avoids unwanted impacts. Many ad-hoc approaches exist, but fundamental science of sustainability is still lacking or in its infancy. We have started to focus on biologically inspired design as an approach to environmentally sustainable engineering. In a biologically inspired approach, a designer abstracts ideas and principles from Nature. Many researchers have adopted bio-mimetic design, but we prefer to be inspired by biology rather than copy it. Some researchers and designer use the abstracted principle or idea with the goal of producing an environmentally superior design, but this is not always the case. In our work, we have started to focus on identifying underlying principles for sustainability [10-13]. Given life’s success and long history of persistence, it is logical to turn to the living world for guidance when attempting to engineer sustainable products, processes and systems.

Consider the issue of dirt or metallic shavings adhering to car parts. Rather than blasting the parts with water, one can ask “how do biological systems handle this problem of dirt protection?” It turns out, that Nature has figured out that a combination of nano-bump surfaces with hydrophobic materials is an excellent strategy to prevent fouling of foreign particles such as dirt, parasites, etc., resulting in what many call “self cleaning” surfaces.

Self-cleaning surface technology inspired by observations of organism surfaces is one example. To appreciate the potential benefits of self-cleaning surfaces, one must understand the biological phenomenon. Micro-and nano-scale surface roughness features combine with hydrophobic surface chemistries to generate the self-cleaning phenomenon. These changes create highly hydrophobic surfaces which cause water to “bead,” as shown in Figure 6.



Drop of water on uncoated (left) versus coated hydrophobic surface (right)

Effectiveness of water cleaning on a plain Aluminum surface (left) and one with a self-cleaning coating (right)

Figure 6: Water on untreated and self-cleaning aluminum [10]

The beaded water quickly leaves the surface of an organism, taking contaminants with it. The self-cleaning ability is called the “Lotus Effect,” in honor of the first plant observed to exhibit it [14]. Interestingly, many other organisms use hydrophobic, micro/nano-rough surfaces to achieve self-cleaning. In a study of 200 plant species, the majority exhibited highly hydrophobic [15]. Wing surfaces of many insect species possess hydrophobic properties and self-clean. Gecko feet exhibit self-cleaning properties which surprisingly help maintain the adhesive abilities of their feet. Even higher organisms such as Pilot whales have micro- and nano-scale surface features. These skin features prevent biofoulers from accumulating and affecting the whale’s hydrodynamics [10, 13].

Soiling and cleaning an aluminium surface coated with a hydrophobic film meant to mimic the "Lotus Effect" illustrates the phenomenon (See Figure 4). On the uncoated side, the water runs over the contaminants, while on the self-cleaning side, the water removes contaminants as it rolls off the surface. Water easily removes contaminants from the self-cleaning side, but the uncoated side may need more intensive cleaning. By showing the difference in required cleaning resources, this simple demonstration illustrates that self-cleaning surfaces hold potential environmental benefits and could replace more energy and material intensive industrial cleaning methods.

Clearly, this approach sounds great if one wants to remove dirt from surfaces with minimal water use. Nevertheless, a life-cycle perspective indicates unintended consequences. When an LCA was performed on different ways to produce a nano-rough surface needed for self-cleaning properties, our findings suggested that one should be cautious with producing self-cleaning surfaces [10, 16, 17]. As show in Figure 7, significant amounts of water are needed to produce 1 square meter of surface (left bars) compared to what it takes to clean such a surface using conventional industrial cleaning systems (right bars). In fact, the amount of water needed to create a nano-rough surface using laser ablation is equal to the water used in 7 cleaning cycles using industrial cleaning technology with 12 liter spray. Chemical and anodized coating manufacturing fares much worse. Clearly, one should be careful in examining the "water return on investment" of producing these self-cleaning surfaces.

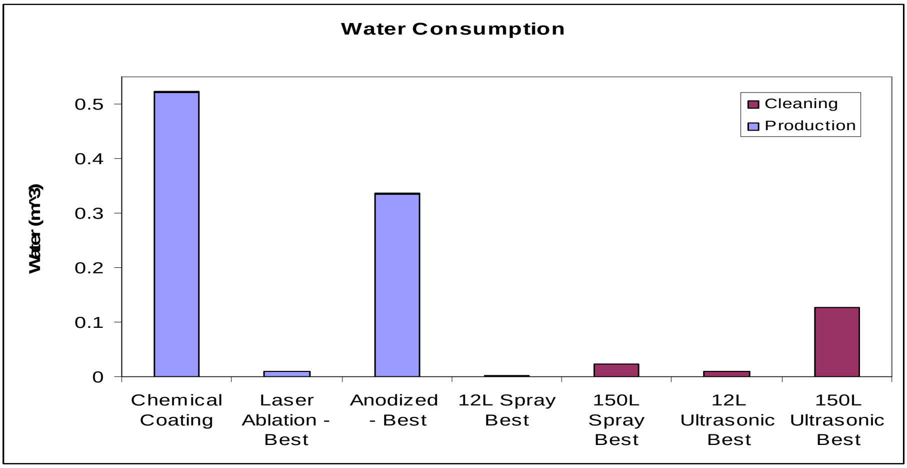


Figure 7 – Water needed to produce 1 m^2 self-cleaning and clean 1 m^2 surface [17]

4 GOING BEYOND PRODUCTS – MANUFACTURING NETWORKS AND ECOSYSTEMS

A major component of sustainable product development is closed loop thinking. End of life directives and initiatives have led to increased recycling of products and materials, but designing a recycling network is still a daunting task. Here too we can learn from Nature.

Research on industrial networks in the field of industrial ecology focuses on industrial symbioses and material flow analysis (MFA). Industrial symbioses, also known as eco-industrial parks (EIP), attempt to embody the "waste equals food" concept found in Naure. They occur when multiple firms or facilities in a bounded geographic area achieve higher system efficiency through the exchange of "waste" energy and materials. Industrial ecologists trace the inspiration for this type of inter-firm cooperation to the biological ideas of mutualism and food web exchanges [18, 19]. The most famous of these developed over the course of many years in Kalundborg, Denmark [20]. While not common, many others have been proposed, developed and even discovered since the identification of Kalundborg [21].

In the last four decades, researchers in ecology taking theoretical, experimental and empirical approaches to food and mutualist web analysis identified multiple network structures, constraints and other characteristics. These structures and patterns decisively contribute to the emergence of network functions and properties. Energy distribution and material cycling through trophic flows have long been known to be important functions of ecological networks, and network architecture influences them. Properties of food and mutualist webs such as dynamic stability (resilience to perturbations in species population sizes) and static stability (robustness to species loss) depend critically upon network topology and the strength of network forming links. While a range of interpretations of the available data exists, those researching the biosphere's interaction webs agree that *1)* ecological networks possess unique structures that clearly deviate from random assemblages and *2)* ecological network topology and link characteristics, network architecture, strongly influences overall network functions and properties such as cycling and stability.

Ecologists employ a host of metrics when analyzing interaction web structures and dynamics. These metrics fall into three categories: static structural, web dynamics and structural dynamics. Static structural measures and metrics focus solely on network structure and provide information about patterns formed by links between nodes at a particular time. The focus on abstract structure permits direct application to industrial networks. In fact, Hardy compared ecosystem connectance values with those of industrial ecologies and eco-industrial parks [18]. Knowledge of the total number of links (L) and nodes (S) in an entire network or particular areas of a network permits their calculation.

Metrics accounting for web dynamics focus on rates of change within a given structure of nodes and links and incorporate steady-state and transient dynamics. Steady-state web dynamics metrics for material and energy flows are based on input-output mathematics originally developed by Leontief for economic analyses. Since they deal with physical quantities common to both ecological and industrial networks, these metrics directly apply to industrial situations. For steady-state material flows, Bailey translated these ecological metrics into industrial equivalents [22, 23]. Transient dynamics modeling first occurred in a complete form in May's work on system stability [24]. In these models, one calculates eigenvalues for interaction matrices to learn a particular community's stability. Negative eigenvalues indicate a community's ability to return to equilibrium if perturbed while positive values indicate the opposite. Interaction strengths represent the effect of one species on the growth rate of another. In this context, stability refers to the viability of species populations that constitute the nodes linked together by interaction strengths.

To create a true industrial "ecology, one should design industrial networks using ecological metrics and values. A manufacturer subject to "take-back" legislation or interested in cutting input material costs with Re-X (reuse, remanufacture, recycle) strategies could optimize or at least compare the environmental character of its planned re-X network using such metrics and values. Those crafting national or international policies may also wish to use these types of metrics to help evaluate the environmental consequences of industrial policies. Initial findings in [13] suggest that current industrial ecosystems are still inferior to well functioning natural ecosystems. Our findings, however, also suggest that it is possible to design and/or improve a recycling network using ecological metrics and goals, and that the result correlates with a financially superior solution [13].

IN CLOSING

To summarize, when dealing with sustainability issues, we believe it is critical to follow a systems approach that includes life-cycle thinking, closed loop thinking, multi-scale/multi-level modeling, and (although not discussed in this paper) understanding user behavior. Failure to do so may lead to suboptimal improvements and unintended negative consequences.

ACKNOWLEDGEMENTS

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