Challenges for the Manufacturing Enterprise to Achieve Sustainable Development

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Abstract
Manufacturing enterprises are striving to achieve sustainability through changes in products, processes, and systems. Decision-support tools and methods are rooted not only in improving environmental aspects of manufacturing, but also in ensuring long-term productivity and social well-being. Refocused efforts on the development of sustainable technologies can further aid continuous improvement and stimulate revolutionary advancements industry-wide. Current and future challenges facing the manufacturing industry are addressed in terms of manufacturing enterprise, product life cycle design, and manufacturing processes and systems. Opportunities for future research are discussed within each of these areas.

Keywords: Sustainability; Life Cycle; Manufacturing

1 INTRODUCTION

Industry has been forced to evolve in the past in response to new regulations, technologies, and changing customer demands. At the dawn of the 21st century, there are increasing concerns about the sustainability of activities in developing nations and the industrialized world. Sustainable development calls for practices and decisions that will ensure that future generations have access to same opportunities that we presently enjoy [1]. For how long can we continue as a global society to extract natural resources, consume energy, and generate wastes with little thought for future generations? In response to growing concern for the environment, our assistance as technologists is needed to support corporate decisions related to manufacturing enterprises and product/process design all directed at helping to realize a sustainable future.

Sustainability is a globally emerging concept for that recognizes the interdependence of the economy, society, and the environment, frequently referred to as the three pillars of sustainability. Businesses are encountering increasing pressure from consumers, governments, and other organizations to address dimensions of sustainability, and increasingly, this involves more than such traditional measures of performance price and quality. Companies have begun to seriously consider product stewardship, reduction of hazardous substances, carbon footprint, energy and water consumption; and their role in society. Governments are instituting policies and companies are establishing strategies to support progress toward achieving sustainability. These policies and strategies serve as drivers for change, and many corporations have begun to critically examine their traditional practices. Manufacturers who do not evolve in response to these drivers will ultimately fall prey to global competitors who are operating under an evolving rule-set.

In particular, many recent concerns have focused on the continuing reliance on fossil fuel-based energy. Not only is accelerated use of non-renewable fuels unsustainable, but combustion results in high levels of carbon dioxide (CO_2) emissions. CO_2 has been linked to climate change, and efforts are underway to reduce its emission to the atmosphere [2]. Figure 1 shows that unless changes are made, carbon emissions will continue to increase, and in less than a century will be nearly ten-fold the current level. Industry remains a large end-use consumer of energy; in the United States it is responsible for about one-third of the total energy demand [3]. The manufacturing sector has a responsibility to reduce energy consumption as well as undertake other efforts to ensure a sustainable future.

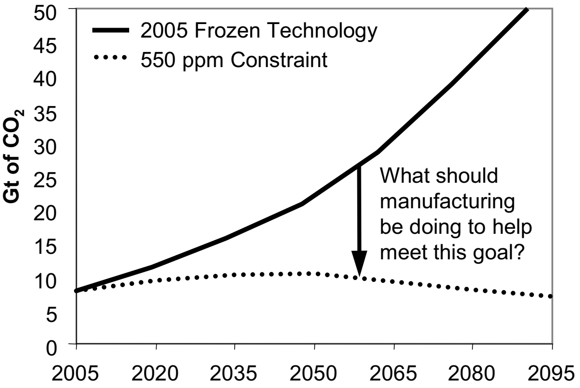

Figure 1: Carbon emissions under two scenarios: with frozen technology and with technology required to achieve 550 ppm concentration of atmospheric CO_2 [2].

This paper begins to explore some of the sustainability-related challenges associated with manufacturing. These challenges will be presented in the context of the following areas: the manufacturing enterprise, product life cycle design, and manufacturing processes and systems. As a starting point for discussion, for each area, some goals for the research community are proposed.

2 MANUFACTURING ENTERPRISES ISSUES

It is increasingly the case that companies are accountable for sustainability-related impacts outside their direct control, including the impacts of supply chain partners. Companies are more and more frequently asking how to select partners that practice sustainability principles or who are socially responsible. What motivates this interest? As one example, it is becoming ever clearer that at some point in the not-to-distant future, embedded energy or carbon of materials and products will be taxed, regulated, or otherwise valued as part of costs. As a guide for supply chain-related decisions, it is believed the following issues must be addressed:

Standard measures for evaluating sustainability performance. As has been noted, corporations have much experience in considering such traditional metrics as cost, quality, and time to delivery in making supplier decisions. There is growing interest in the use of environmental metrics to describe corporate performance, and ISO 14000 certification represents an important first step in standardizing the methods by which all companies approach environmental sustainability. The Global Reporting Initiative has improved sustainability reporting through efforts aimed at standardization and transparency [4]. However, even for companies aware of their corporate-wide environmental footprint, it is very difficult to disaggregate this environmental information based on the materials, components, and products that they may produce. Standard eco-measures for products and processes are needed. In terms of societal sustainability, ISO 26000 is still several years away from being released. Still, it seems likely that formulating socio-measures of performance at the product/process level will be even more challenging than developing eco-measures.

Method for integrating the sustainability-related impacts of all the contributions to a product from a supply chain. Manufacturers create products using components/materials obtained from suppliers and through value-added operations performed on components and materials. Assuming that eco- and socio-measures of performance can be defined and quantified for each component, at issue is how to integrate these measures for the product. Hutchins and Sutherland [5] have discussed this issue and proposed a scheme that weights supplier performance measures by the economic value the supplier-delivered component contributes to the product; the scheme also incorporates the value-weighted performance of the manufacturer itself.

Development of EOUP (end-of-use product) management strategies and associated logistics. As corporations contemplate a future where used products are recovered and returned for recycling and remanufacturing, increased attention must be given to tracking the “inventory” and status of products that are currently being used. Moreover, consideration must be given to the best manner to recover and transport these EOUPs for subsequent processing [6].

The foregoing discussion highlights the fact that there are significant technical challenges that must be addressed to establish meaningful measures of sustainability performance as well as a method for the integration of these measures. An emerging paradigm shift in the notion of how used products are managed will drive many enterprise changes, and will require increased use of life cycle thinking to ensure that any action taken is not counter-productive. It should be evident that the record-keeping associated with such ventures will be significant.

3 PRODUCT DESIGN ISSUES

Products should be designed to respond to the needs of consumers. In the 21st century, the challenge of sustainability suggests that designers must also factor the environment and broader social interests into their decisions. It is now well recognized that designers should consider the entire product life cycle in this decision-making process.

Can we continue to tolerate a situation where waste is “designed into” products? Where manufacturing processes consume vast amounts of energy and materials and produce waste of all forms? Where used products are disposed with little regard to potential environmental impact and value lost? The traditional life cycle includes materials extraction and processing, manufacturing, distribution, use, and end-of-life stages. End-of-life for many products means disposal/landfilling. Figure 2 suggests a product life cycle to which we should aspire. Green design is employed to reduce environmental impacts across the life cycle, green manufacturing processes are used that require little energy and emit zero wastes, and preventative maintenance is employed to extend product life. The figure shows EOUPs being recovered for reuse, remanufacturing, and recycling.

3.1 Life cycle assessment

Any meaningful progress in terms of product design that promotes sustainability will require a life cycle assessment (LCA). A research challenge associated with this category is

Improvement of LCA methods and software tools. This challenge includes progress on identifying appropriate allocation schemes, guidelines for performing streamlined LCAs, and improved data quality. Gaps are present within existing tools and these must be identified and filled (e.g., not enough manufacturing process-specific information). Not enough is known about the uncertainties and risks embedded within LCA methods and data, and thus on the reliability of the methods themselves. Methods and data are needed for both environmental LCAs and societal LCAs.

As noted previously, weighting of various impacts requires consideration of trade-off analysis methods to simultaneously consider economic, social, and environmental issues.

3.2 Material selection

Material selection is a key element of design, and thus will have a significant effect on sustainability. Guidelines have been developed for the selection of materials [7] [8]. They often are general and do not provide the necessary specificity that designers require.

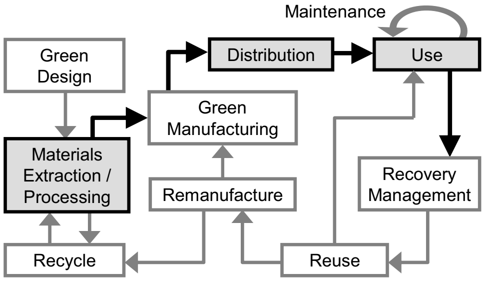

Figure 2: Product life cycle incorporating green design and manufacturing and used product recovery management.

Table 1: Embedded (processing) energy estimates of selected engineering materials (MJ/kg), adapted from [9].

Material	MJ/kg
Aluminum, virgin (recycled)	191 (8.1)
Float glass	15.9
Polypropylene	64.0
Steel, virgin (recycled)	32.0 (10.1)

The following is offered as a research challenge in the area of material selection:

Development of improved materials data for a variety of metrics. Some data are available on the environmental characteristics of materials, but the quality of these data may be suspect, and much property-related data is missing (e.g., energy consumed, waste produced, and water used per unit mass; recyclability; and biodegradability). Considerable progress is needed to tie materials level issues to such societal level issues as education, healthcare, and equity.

Furthermore, the sparse data that are available may be misleading. Table 1 provides estimates of embodied energy for several engineering materials; the values do not include manufacturing energy requirements. The table reveals large energy benefits associated with recycled aluminum and steel and suggests that aluminum is a superior alternative to steel. However, it must be remembered that the embedded energy of a recycled aluminum product must also reflect the significant energy required to process the virgin aluminum.

3.3 Design for the environment

Design for the environment (DFE) encompasses strategies and techniques aimed at reducing environmental impacts through such efforts as extending product life, reducing use-stage environmental burdens, and facilitating post-use recovery, reuse, recycling, and remanufacturing. Research challenges related to DFE include the following:

Increased emphasis on modular design. This philosophy calls for modular, upgradeable platforms that reduce impacts through integration of recovered end-of-use components. Modules should be defined across platforms and product generations, and yet not limit design flexibility. Much work is needed in the general area of design modularity; improved knowledge of returning component availability and condition is also required. Modularity offers a significant manufacturing benefit and supports mass customization. Of course, as in all design-related decisions, modular design should be guided based on life cycle assessment knowledge.

Renewed attention to product dematerialization and service-oriented products. Environmental impact is virtually proportional to the amount of material in many products, e.g., fuel consumption of an automobile is proportional to its mass. Dematerialization calls for the development of products that employ less total material in meeting consumer needs. Methods for dematerialization include more efficient product designs, better materials, and transitioning from a tangible (material-based) product to a service (an intangible product) [10]. While efforts have been underway for decades to develop more material efficient product designs, the concept of integrated product-service systems that have a high service content is more recent phenomenon and is only beginning to receive attention from the research community.

Of course, the research challenges identified represent only two DFE issues, and many others exist. The principle of sustainability embraces societal issues, thus an analogous companion to DFE would be the philosophy of Design for Society. Presumably, DFS would be focused on developing integrated product-service systems that in addition to satisfying consumer needs, also address broader societal concerns. The creation of products for the developing world using appropriate technology is one example of DFS.

4 MANUFACTURING PROCESSES AND SYSTEMS ISSUES

Across their life cycles, products consume large levels of resources and produce substantial wastes. An automobile consumes nearly 1 TJ of energy across its life cycle [11]. While most of this energy is associated with vehicle use, about 125 MJ is expended in materials processing and manufacturing – and this happens over a relatively short time period. Williams [12] reported the majority of the life cycle energy associated with a desktop computer is attributable to manufacturing (81%). Clearly, manufacturing processes have a significant eco-footprint that requires attention.

In an era of increased attention to recycling and remanufacturing, more focus should be directed at the processes employed for these activities. Important challenges related to the manufacturing of virgin and used products exist and these challenges may be classified based on whether they are associated with virgin products (manufacturing processes) or used products (recovery processes). Systems-oriented challenges are also present for both classes. The text below presents some thoughts on the challenges associated with these two classes.

4.1 Manufacturing processes

Our goal for manufacturing processes should be to establish processes that consume very little energy and produce zero or near-zero waste. Moreover, in support of product and process design efforts, information on existing and proposed manufacturing processes needs to be available that relates process inputs to environmental impacts. The following challenges are proposed:

Establish improved information on the environmental impacts of existing manufacturing processes and explore new technological concepts for greener operations. In support of product and process design, and life cycle assessment, the environmental impacts (resources consumed and wastes produced) by manufacturing need to be better quantified. Where good data exists, it is often aggregated and difficult to allocate to a single operation. New processes and technologies need to be established that avoid the traps (and wastes) of traditional operations; for example, we need to identify techniques for eliminating material removal operations, perhaps via additive operations.

Development of systems that can accommodate the use of mixed manufactured and remanufactured components. As we consider manufacturing systems of the future, it may be that both manufacturing and remanufacturing operations are housed in the same facility. Manufacturing processes will produce virgin components and remanufacturing operations will process used components, perhaps with both flows of components flowing into products. Clearly, such a situation will require the development of new approaches to manufacturing system design and operations to accommodate the significant differences between manufacturing and remanufacturing.

4.2 Recovery processes

Recovery processes are essentially those processes used to transform a used product into a component or material that can be re-integrated into a product. In essence, recovery processes include dismantling, sorting, remanufacturing, and recycling operations. Proposed research challenges associated with recovery processes include:

Development of recovery process knowledge and technologies. Improved knowledge is required for all steps in the processing of a used product into either a refurbished component or material that can be formed into a component. This includes inspection, dismantling, sortation, purification, remanufacturing, and recycling processes. At issue is acquiring fundamental insights into the physics of the operations, with particular emphasis placed on the understanding how environmental impacts depend on process inputs. One key challenge is identifying, based upon inspection, whether to recycle or remanufacture a used product, early during the recovery process before additional costly activities are undertaken. A continuing concern will be to develop effective recycling and remanufacturing processes.

Establishment of better manufacturing systems for recycling and remanufacturing. At a systems level, methods are needed that are less labor intensive and more flexible. For example, it would be ideal if dismantling facilities could disassemble a diverse variety of products.

As a general comment, while much work has been performed to characterize manufacturing operations and improve their performance, little of this work has been directed at environment-related issues. Many issues remain to be investigated.

5 SUMMARY AND CONCLUSIONS

Many individuals now believe that we are entering a sustainability revolution, and this revolution will present us with many issues to be addressed. The manufacturing research community needs to recognize that sustainability issues need to be addressed and critically examine all elements of the processes and systems for which we are responsible – what should we be doing to help achieve sustainable development? As a starting point for discussions, this paper has proposed several challenges for the manufacturing enterprise that we should consider as we contemplate the future:

- Standard measures for evaluating sustainability performance.
- Method for integrating the sustainability-related impacts of all the contributions to a product from a supply chain.
- EOUP management strategies and associated logistics.
- LCA methods and software tools.
- Improved materials data for a variety of metrics.
- Emphasis on modular design.
- Product dematerialization and in particular, service-oriented products.
- Information on the environmental impacts of existing manufacturing processes and new technological concepts for greener operations.
- Systems that can accommodate the use of mixed manufactured and remanufactured components.
- Recovery process knowledge and technologies.
- Better manufacturing systems for recycling and remanufacturing.

Additional interaction on these and other issues is welcomed and needed. After all, the stakes are high. Unless appropriate actions are taken, we run the risk of jeopardizing our future.

6 ACKNOWLEDGEMENTS

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