Life Cycle Engineering and Sustainable Manufacturing

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When Frosch and Gallopolous published their seminal article "Strategies for Manufacturing" in 1989, they signaled a central concern with manufacturing in the field of industrial ecology (IE). They and other early pioneers in the field brought an interest in examining how industry could leverage its technological prowess to improve environmental outcomes. In North America, this interest emerged, in part, from the extraordinary complexity and expense in environmental remediation of the legacy of past industrial practices. Superfund, as the widely contested U.S. remediation law is called, led many to want to "do it right from the get-go" and to move away from end-of-pipe strategies. This naturally led to an interest in design for environment (DfE) as a means to anticipate and avoid polluting processes and products. Also, DfE entails engagement with production and manufacturing.

With this special issue, we seek to make a modest contribution to grappling with . . . the lack of communication between the life cycle engineering and industrial ecology communities] by presenting research on the sustainable manufacturing and the role of life cycle engineering in the Journal of Industrial Ecology. As the life cycle engineering and sustainable manufacturing concept further evolves, it is important that the manufacturing community expand their boundaries to consider their collective impacts at larger scales. At the same time, industrial ecology can benefit from the deep technical knowledge possessed by the manufacturing disciple

In the United States, engineering had a prominent role in the development of the field. IE gained much of its impetus from the U.S. National Academy of Engineering (NAE). The NAE organized the colloquium in 1991 that resulted in the seminal set of articles in the *Proceedings of the National Academy of Sciences* that helped launch the field (Jelinski et al. 1992). The NAE then published six books on IE[1] with titles such as *Engineering within Ecological Constraints* (Schulze and National Academy of Engineering 1996) clearly indicating the centrality of engineering. In the same vein, articles in this journal included DfE studies reflecting the interest of the pioneers in how production-related processes could leverage environmental improvements throughout the product life cycle (PLC) (e.g., Carnahan and Thurston 1998). There was, and is, an ongoing attention in this respect to the electronics industry reflecting the background of some of the key pioneers in the field, notably those coming from AT&T and Bell Labs (Graedel and Allenby 1998). Another important cornerstone in the development occurred in 1999 when the U.S. National Science Foundation (NSF) and the U.S. Department of Energy formed a panel for an international study of "environmentally benign manufacturing." This led to a significant initiative by the NSF, under the leadership of Delcie Durham, to fund new studies in this fledgling area (WTEC et al. 2001). [2,3]

Thus, manufacturing engineers further explored paths to steer manufacturing toward sustainability. Whereas at the same time IE grew and its scope broadened, the attention to manufacturing per se was eclipsed by interest in subjects such as sustainable consumption and urban metabolism. Further, even in "Strategies for Manufacturing" (Frosch and Gallopoulos 1989), the focus was on manufacturing in the context of the entire PLC or between factories exchanging by-products outside of the typical production chain.[4]

Thus, IE has strong roots in engineering and industry, both in terms of its methods and the people who comprise its community. Despite these characteristics, IE has had only modest interaction with the community and literature of manufacturing engineering. When the focus is narrowed to the topic of this special issue—life cycle engineering (LCE) and sustainable manufacturing—the disconnect is even more puzzling, given the centrality of life cycle thinking to IE. Some people have been active in both communities, as is the case with two of the editors of this special issue (Gutowski and Hauschild).

Given this disconnect, some background on LCE and sustainable manufacturing is appropriate here. The focus on the entire life cycle of products from a production engineering perspective started mainly in the late 1980s and early 1990s. The reasons were manifold and quite familiar to the readers of this journal. On the one hand, the emerging approach was grounded in environmental concerns related to damages to the natural environment and people, and an increasing amount of waste as well as the depletion of nonrenewable resources. On the other hand, it became visible that end-of-pipe solutions have limits.

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Also, predictions of a dramatic increase of the world population over the next 50 years combined with economic growth raised concerns about the natural capacity of the planet. With the publication of the final report, *Our Common Future*, of the World Commission of Environment and Development in 1987, the urgency of action spread outside the narrow circles of environmental scientists and nongovernmental organizations. Instead of focusing on cleaner technologies, the role of eco-design in shaping the sustainability of manufactured products became clear to leading researchers within manufacturing engineering. In 1991, Leo Alting, one of the pioneers in Europe, presented his vision of life cycle design (LCD) and formulated the basic ideas on the PLC concept (Alting 1991).[5] In the same year, he also convinced the Danish Environmental Protection Agency to finance a large project in environmental design of industrial products. Just one year later, he and others succeeded in starting a life cycle group in CIRP (the International Academy on Production Engineering) (Alting 2014). The result, as readers of this journal know, was that a rethinking of business and striving toward "sustainable industrial production" became a hot topic also in the manufacturing community (Alting and Jørgensen 1993).

Researchers at that time highlighted the importance of both the product development stage as a key life cycle stage and the necessity to evaluate the impact of design alternatives in support of decision making during product development. Emerging areas were design for service, for instance, addressing ease of repair during product use, as well as design for disassembly and recycling, addressing the challenges related to the end of life (EOL) of products. General design guidelines were published (Boothroyd and Alting 1992) and software tools were developed, able to calculate characteristic results, such as disassembly and recycling cost based on different depths of disassembly (Chen et al. 1993; Ishii 1995). To evaluate environmental impacts, life cycle assessment (LCA) in particular was adopted to support decision making (Alting and Jørgensen 1993). The terms LCD and LCE were introduced to promote a simultaneous consideration of all PLC stages from production to EOL within the product development (Alting 1991; Alting and Legarth 1995). Because LCE encompassed various approaches then as now, no agreed-upon definition emerged. An early definition provided by Alting and Legarth (1995, 570) still gets to the heart of the matter:

> Life cycle engineering is the art of designing the product life cycle through choices about product concept, structure, materials and processes, and life cycle assessment (LCA) is the tool that visualizes the environmental and resource consequences of these choices.

Where LCE expresses the important leverage of product development, the term sustainable production has been used to show that "the manufacturing community is facing a strong requirement of sustainability" (Alting and Jørgensen 1993, 167) and solutions going beyond the development of products are required to address the above-mentioned motivation. The definition provided by Alting and Jørgensen (1993, 167) is still widely used:

> Sustainable production means that products are designed, produced, distributed, used and disposed with minimal (or none) environmental and occupational health damages, and with minimal use of resources (materials and energy).

Today, several research areas can be identified that evolved from these origins. Life cycle planning has introduced enhancements in LCE (product design) through a design of the material flows along the life cycle. Within life cycle planning, the product concept, alternative life cycle options, and suitable business models are systematically elaborated (Umeda et al. 2012). With focus on the manufacturing stage, energy and resource efficiency have been analyzed at all levels from a unit process to a multimachine/process chain to the factory up to a multifactory and supply-chain level (Bakshi et al. 2011; Duflou et al. 2012). Common ground for these approaches is provided by established methods, and tools such as LCA and life cycle costing are discussed and used. Moreover, several new methods and tools have been developed, making use of the latest modeling and simulation techniques and enabling the investigation of more-complex systems with their dynamic interdependencies. In addition, various approaches and technologies have been developed, addressing specific issues of a PLC such as serviceability, reuse, and remanufacturing (Kara et al. 2005; Sutherland et al. 2008). An overview of the field is provided in a recent textbook by Dornfeld reviewed in this issue by Kaebernick (2014).

Thus, when taking a quick glance at the history of the development and definition of LCE, it appears that the overall motivation does not differ much from the reasons for the emergence of IE mentioned in the beginning of this editorial, and the link between the presented definitions for LCE and sustainable production becomes obvious. The intersection between LCE and industrial ecology is also illustrated by research articles related to both LCE and sustainability in manufacturing published by the *Journal of Industrial Ecology* throughout its history (e.g., Carnahan and Thurston 1998; Chang and Allen 1997; Masanet 2010; Sullivan et al. 2013; Baumers et al. 2013). A main difference between the dominant understanding in LCE and sustainable production and the concept of IE is that the latter "requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them" (Graedel and Allenby 2010, 32) and that activities are considered to "change the story" instead of striving for "a little less bad" (Graedel and Allenby 2010, 113) or for efficiency only.

In the course of this development, a variety of new terms have been introduced and promoted, such as environmental engineering, environmentally benign manufacturing, green engineering, green chemistry, closed loop manufacturing, design for environment, eco-design, life cycle management, and sustainable engineering. Therefore, it is not always easy to infer the content of an article from the terminology used in the title. At the same time, it has to be questioned whether disciplines should be narrowed or differentiated from each other or whether there is a need to structure the variety of the different approaches and simultaneously, jointly, develop a shared understanding. Yearning for a definite, comprehensive view of a wide area of related research fields has been a goal in science for a long time. In 1932, Albert Einstein fittingly remarked on the occasion of Arnold Berliner's 70th birthday, then editor of the journal *Naturwissenschaften* (*Natural Sciences*):

> It was inevitable that the activity of the individual researcher must retreat to an ever more limited sector of the total knowledge. It is even worse that this specialization implies that the mere general understanding of total science [. . .] can hardly keep up with the development. This creates a situation similar to that which is represented symbolically in the Bible in the story of the Tower of Babel.[6]

Many interested in the area of life cycle engineering and sustainable production as well as industrial ecology have recognized this situation and worked on schemes to structure and relate the different research fields (see, for example, Coulter et al. 1995; Graedel and Allenby 2010; Westkämper et al. 2000). Nonetheless, the disciplines that should collaborate prefer to publish in "their" community, and only a few authors cross the "boundaries" or enjoy the "edge effect." In other words, we still have to overcome a "serious cultural problem" (Erkman 1997, 7).

With this special issue, we seek to make a modest contribution to grappling with that cultural problem by presenting research on sustainable manufacturing and the role of LCE in the *Journal of Industrial Ecology*. In doing so, we want to encourage an interdisciplinary discussion. Therefore, contributions from industrial ecologists, manufacturing and design engineers, production and operations researchers, economists, and environmental scientists with an interest in sustainable manufacturing were invited. The articles address research, conceptual frameworks, applied tools, and case studies from different industries. On the one hand, they show the broadness of LCE and sustainable production spanning from product design to product remanufacturing. On the other hand, they show the complex decision problems that ask for supporting methods and tools.

From Product Design . . .

At the product design stage, not only the main product attributes are decided (product structure, materials, and joining techniques), but also the greater part of the environmental impact from the subsequent life cycle stages (manufacturing, use, disassembly, reuse, remanufacturing, and recycling) is largely predetermined. The majority of design tasks today start from an already existing product or design. To support decision making, methods and tools are used that allow a comparison of the "old product" with the "new product" or a comparison of design alternatives (e.g., alternative materials). Therefore, designing a product asks for appropriate evaluation methods and tools. In their article, Shuaib and colleagues (2014) present a methodology to assess the sustainability performance of a product taking all three dimensions of sustainability into account. The methodology is based on a multicriteria evaluation considering various metrics. An overview of previous work on sustainability assessment at a product level is provided and the development methodology is explained in detail. A consumer electronic product is used as a case study and to demonstrate the applicability of the methodology.

Material selection is one of the key aspects when it comes to sustainability for many products. To fulfill the distinguished product requirements (e.g., mechanical, electrical, thermal, and cost), various material properties (e.g., yield strength and heat conductivity) have to be analyzed while taking the environmental impacts of the alternative materials into account. In their article, Tambouratzis and colleagues (2013) look at the resulting complex decision problem in detail. A methodology is presented to support the identification of the best material(s) for a given application. With product properties as input (e.g., mechanical properties, such as Young's modulus) and environmental impacts as output (e.g., carbon dioxide [CO_2] emissions from manufacturing), not only existing materials, but also properties of novel materials with the lowest environmental impact can be identified.

The use stage of a product can be highly relevant with regard to the overall environmental impact during a product's lifetime. Further, the impact often depends very much on how the product is used and maintained. Therefore, in their article, Serna-Mansoux and colleagues (2014) look at the product-user interaction and at design strategies influencing consumer behavior during the use stage. To steer the behavior of the user, additional product features, such as labels or displays, can be used. However, the user may get accustomed to the information or feedback. Further, the environmental impact resulting from the addition of such a feature has to be quantified to avoid negative trade-offs. To address these, the researchers model the product-user interaction and the behavior change over time, introducing a so-called mitigation rate. The environmental impact of the product and the amount of consumables are quantified by applying LCA. The importance of the use stage is not limited to products that use energy and/or material directly. Sanyé-Mengual and colleagues (2014) show, in a complementary article, that the maintenance of products and the means used for it have to be considered in both product design and communication-to-user strategies. LCA is used to evaluate different maintenance alternatives and derive a communication strategy based on the results.

DfE can be used to improve not only consumer products, but also industrial products. In their article, Schischke and colleagues (2014) look at the energy and resource efficiency of industrial equipment and, more specifically, at welding equipment based on the eco-design requirements derived from the European Ecodesign Framework Directive, which currently also addresses production equipment, including ovens, furnaces, machine tools, and related machinery. A significant energy savings potential of 7.6 petajoules per year has been identified for this field, and challenges and limitations to realizing these potentials are discussed.

In general, the product design process can be divided into a conceptual design stage and a detailed design stage. The latter is usually supported by using computer aided design (CAD) tools. Since the first developments in LCE or DfE, there have been discussions as to which features from LCE/DfE should be integrated into CAD tools versus staying as a standalone tool supporting environmental experts as part of an interdisciplinary team.

To avoid uncontrolled diffusion of toxic materials into other material flows during material processing in EOL, components containing toxic materials should be disassembled and treated separately. In their article, Chang and Lu (2014) present a concept for an integrated evaluation of material toxicity and ease of disassembly as part of CAD software. The evaluation of the material toxicity is based on the concept of toxic potential indicators (TPIs) and is adapted for use with a Taiwanese TPI database, furthering work that links TPI with Taiwanese data published in this journal (Yen and Chen 2009). To steer the design process, four characteristic values are calculated and linked with design suggestions. A music player device is used as a case study to demonstrate the developed concept and the software prototype.

. . . to Manufacturing and Remanufacturing

The energy consumption of a manufacturing system results from the machines involved and is highly dynamic as a result of the fact that the energy consumption depends on the machine status and the machines are interconnected. Simulation models are proposed to address these dynamics and support the design and control of manufacturing systems (Duflou et al. 2012). Wang and colleagues (2014) look at the energy consumption of flexible manufacturing systems and investigate the main influencing factors, such as uncertainty of task assignment and changing operation times. An energy model based on colored timed petri nets is developed, allowing simulation experiments and to analyze the energy consumption in detail. Complementary to the article from Wang and colleagues, Cullen reviews a book by Thiede on energy efficiency in manufacturing systems (Cullen 2014). The book provides a systematic approach that allows modeling and simulating energy flows of an entire factory system. The book can serve as a guide for companies aiming to reduce energy demand. Cullen points out questions that are not answered by the book, such as: What should be prioritized or what actions could be taken in which manufacturing sectors?

An important part of LCE is the management of products at end of life. Retrieving EOL products from users is an important part of that process. Souza (2014) reviews an edited collection on the design of reverse supply chains, focused on mathematical models that provide decision support from the perspective of profit maximization or cost minimization. Souza points out that these models are limited in their environmental dimensions, and "that gap may provide opportunities for collaboration" between industrial engineers involved in reverse supply chains and industrial ecologists. Once manufactured products reach EOL, two main options are available: recover the materials or the functional value. Remanufacturing aims at restoring old products to a condition equal to new products not only in terms of functionality, but also with regard to warranty. Several studies have shown the environmental benefits of having remanufactured products replace new products (Smith and Keoleian 2004). However, various drivers and barriers have to be taken into account when considering remanufacturing as an EOL (Smith and Keoleian 2004) strategy. As an example, short technology innovation cycles are an obstacle to some remanufactured products (Gutowski et al. 2011). After centuries with manufacturing being dominated by Western countries, China has emerged as one of the largest manufacturers in the world. Accompanying the rapid growth, material shortages have become a concern, together with rapidly growing waste streams not only in research, but also in industry and policy making. In their article, Tan and colleagues (2014) review the current degree of development of EOL product remanufacturing in China. Their comprehensive study analyzes the evolution of related policies, standards, research studies, and the remanufacturing industry with special emphasis on the status of remanufacturing of electronic products. Besides short innovation cycles and the need for tools and techniques to evaluate remanufacturability for this product group, they highlight the inadequate system of regulations and standards as well as dominating prejudices among consumers in China. In a complementary article Liu and colleagues (2014) compare the environmental performance of a manufactured and a remanufactured heavy-truck diesel engine in China by applying LCA. The study quantifies the environmental net benefits. However, because the remanufacturing industry in China is still at small scale, the researchers conclude that the Chinese government should step up efforts in supporting the development of the remanufacturing industry in China.

Can We Learn from the Process Industries?

Finally, Jutta Geldermann reviews three books on process improvement and integration, including "pinch" analysis, in the chemical process industries. According to Geldermann (2014), "process integration is a well-established approach for materials and energy flow studies, which have a long tradition in the chemical industry." The application of these tools to the even more stringent demands for resource conservation brought on by our concerns for sustainability is a useful contribution. At the same time, however, as the reviewer implies, these techniques have been practiced routinely for some time and yet they have not led to sustainability. This paradox can serve to highlight the dilemma of sustainable manufacturing: to what extent will it look like yesterday's practices and to what extent will be something totally new.

Closing Comments

This special issue provides a window on research work done in the area of LCE and sustainable manufacturing. The importance of designing a product through informed decisions about the product structure, materials, and joining techniques is highlighted. Approaches to decision support are presented. Sustainable manufacturing goes beyond the product design and asks for contributions toward new methods, tools, and technologies to minimize cost and environmental impact in production, use, and EOL. As the LCE and sustainable manufacturing concept further evolves, it is important that the manufacturing community expand their boundaries to consider their collective impacts at larger scales. At the same time, IE can benefit from the deep technical knowledge possessed by the manufacturing discipline. One example of how these two sorts of expertise can be melded is the analysis of manufacturing conducted by Allwood and colleagues (2010). The analysis focused on the efficiency opportunities available globally to the materials production sector of manufacturing as well as comparing manufacturing's CO_2 emissions to the goals of the Intergovernmental Panel on Climate Change (IPCC). Based on this work, challenges and opportunities for further actions to reduce manufacturing's carbon emissions have been identified (Gutowski et al. 2013). Similarly, the United Nations Environment Program's International Resource Panel has comprehensively examined metal recycling (Graedel et al. 2011) and a promising line of research on materials efficiency has emerged as well (Allwood et al. 2012). The definition of sustainable manufacturing is still far from resolved, as the results from a recent NSF workshop clearly reveal (Huang et al. 2014), but the pursuit of this question is surely an integral part of the larger issue of how to achieve a sustainable society.

Notes

1. For a list of the NAE books, see www.nae.edu/Programs/Environment/PastProjects/IndustrialEcology/IndustrialEcologyRecent NAEPublications.aspx.
2. This effort was significant because it made money available to study EBM that was not tied to a corporate sponsor.
3. This cursory description of the role of manufacturing and engineering in industrial ecology does not reflect some relevant developments in Europe.
4. This difference in perspective can also be seen in the titles that were proposed by Frosch and Gallopolous for their seminal article: "Materials in a Changing Environment" and "Towards an Industrial Ecosystem." Those titles were overruled by the editor of *Scientific American* in favor of "Strategies for Manufacturing" in order to conform with other articles in the special issue in which the industrial ecology article was published (Frosch 2014).
5. The article (Alting) can be also found in a book edited by Kusiak (1993).
6. "So konnte es nicht ausbleiben, dass sich die Aktivität des einzelnen Forschers auf einen immer beschränkteren Sektor des Gesamtwissens zurückziehen muss. Noch schlimmer aber ist es, dass diese Spezialisierung es sogar mit sich bringt, dass auch das bloße allgemeine Verständnis für das Ganze der Wissenschaft [. . .] immer schwieriger mit der Entwicklung Schritt halten kann. Es wird eine Situation geschaffen, ähnlich derjenigen, welche in der Bibel in der Geschichte vom Turm zu Babel symbolisch dargestellt ist."

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