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Establishing Greener Products and Manufacturing Processes

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Today producers are becoming more responsible for their products, not only because of legal requirements but also to gain a competitive edge, as consumers are increasingly considering the broader impacts of their purchases. As a result, companies are beginning to address the ecological impacts of products and manufacturing processes in addition to the economic considerations. The environmental impact of products can be reduced during manufacturing, e.g. by greener processes, greener process chain, or leveraging manufacturing. This paper reviews actual research on greening products and production at the University of California, Berkeley and lays the foundation for future research directions. The present research includes approaches to enhance Life Cycle Assessment Methods, understand the life cycle of different products, improve manufacturing processes and revise supply chain decisions. Leveraging manufacturing implies higher environmental burden in the production phase can be offset with much larger eco-efficiency in the product use phase. The described approaches present ongoing work and will support sustainable production practices.

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NOMENCLATURE

API = Application programming interface
CMOS = Complementary metal oxide semiconductor
GHG = Greenhouse gas
GWP = Global warming potential
LCA = Life Cycle Assessment
LCI = Life Cycle Inventory
Mfg = Manufacturing
MRR = Material removal rate
RoHS = Restriction of Hazardous Substances Directive
WEEE = Waste Electrical and Electronic Equipment Directive

1. Introduction

Today producers are becoming more responsible for their products, not only because of legal requirements but also to gain a competitive edge, as consumers are increasingly considering the broader impacts of their purchases.[1] As a result, companies are focusing increasingly on the ecological impacts of manufacturing processes in addition to the established economic considerations.[2] This requires a fundamental understanding of sustainable, environmentally friendly manufacturing.

Haapala et al. gave a comprehensive review on research in sustainable manufacturing.[2] They highlighted research needs in four categories: i) manufacturing processes and equipment, ii) manufacturing systems, iii) changes in life cycle paradigms, and iv) education. The actual research on greening products and production at the Laboratory for Manufacturing and Sustainability (LMAS) at the University of California, Berkeley addresses all these needs and is described in the following. The research efforts by themselves offer single improvements. Single improvements can be regarded as "technology wedges" which add up to sustainable technology.[3]

The idea of product life cycle is introduced in Section 2 as well as tools to evaluate the environmental impact of products and systems. We highlight how different life cycle assessment tools are chosen, how the metrics and life cycle inventory can be improved and how ongoing research will address existing mismatches.

Section 3 gives examples how product design affects the product life cycle impact and where greening strategies lie. This research fills needs on changes in life cycle paradigms (needs iii in[2]). As one example for a use-phase intensive product, manufacturing equipment is analyzed in detail, meeting research need i) in.[2]

In Section 4 we elaborate research on manufacturing processes

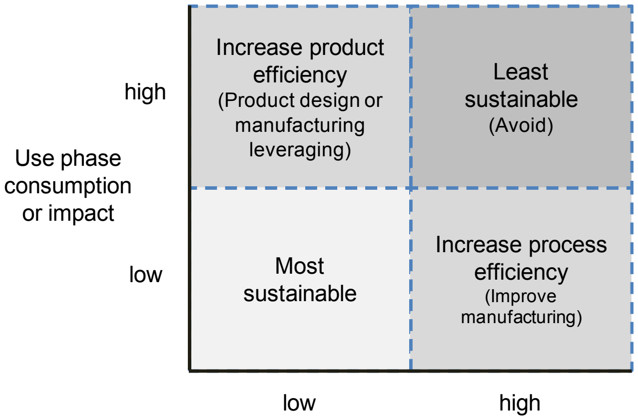

Fig. 1 Impacts in manufacturing vs use phase[5]

addressing need i) as well. Ongoing work on machining, grinding, drilling in Printed Circuit Boards and process planning is presented.

Section 5 concentrates on more levels to production including supply chains, transportation, location and packaging. Research in these areas tackles needs in the area of manufacturing systems (need ii) in[2]). In Section 6 we introduce the concept of leveraging, which means that higher impacts in the manufacturing phase of a product can lead to greatly reduced environmental burden in its use phase. This concept demands a big change in life cycle paradigms (need iii) in[2]), but bears also a huge possibility for higher overall sustainability.

Findings of this research go into the education of students, faculty, staff and industrial partners of The University of California, Berkeley, which tackles need iv) for education. The review in this paper lays foundation and defines future research directions with the potential of greater sustainability. The research at the University of California, Berkeley is not finished yet and is inspired by visionary outlooks, which are also mentioned in this paper.

2. Where to Focus - Products or Manufacturing Processes?

2.1 Product Life Cycle

The product life cycle consists of raw material extraction, production, use and end of life.[4] The environmental impact of these phases often differs depending on the product, for example automotives use most energy in their use phase (possibly more than 80%[4]). In contrast, parking garages have their highest energy demand in the raw material extraction phase (around 90% in[4]). Producers have to identify which phases they will direct their efforts to in order to reduce environmental impacts. Because raw material extraction and end-of-life are defined mostly by product design, production engineers focus on use phase and manufacturing.

Fig. 1 displays these two dimensions of a product. The axes of use and manufacturing phase indicate, from low to high, the consumption or impact associated with that phase of the product's life cycle. The “low-low” quadrant indicates the most sustainable product, whereas the “high-high” quadrant includes products that are to be avoided or offer the most potential for improvement. The remaining quadrants contain products which would benefit from an increase in the efficiency of either use phase or the manufacturing process.[5,6]

The next section of this paper examines an established method to evaluate the environmental impact in the different life cycle phases, Life Cycle Assessment (LCA). The following sections will explain several strategies for higher efficiency and reduced environmental impact.

2.2 Life Cycle Assessment (LCA) and Related Metrics

Over the last decades, many different standards and methodologies were developed to evaluate the environmental impacts of products and manufacturing systems. The most commonly used method is Life Cycle Assessment (LCA), including its variants process LCA, Economic Input-Output LCA and hybrid LCA. The method is addressed in the ISO14040 standard, US EPA Life-Cycle Engineering Standard, and various emerging greenhouse gas protocols.[7] ISO14040 gives a framework to conduct an LCA through definition of the scope, followed by inventory analysis (LCI), then life cycle impact assessment (LCIA) and finally interpretation of the results.

In process LCA the input and output streams in different stages of a product’s life are investigated in detail, often in complicated process-flow diagrams.[7] Economic Input-Output LCA utilizes economic input-output data of a product and includes industry-level data of environmental impacts per dollar sold by an industry.[7] Hybrid LCA joins both approaches to overcome problems in available time, data accuracy and data granularity.[7]

To help with the wide range of LCA methods, Reich-Weiser et al. discussed the differences between frameworks based on review of LCA literature and standards.[7] They sorted the frameworks into different spatial and temporal levels of complexity.

Trade-offs at the factory or machine tool level were found to be best analyzed by process LCA approaches because of the highly detailed data.[7] However, a large amount of data collection is required for a process LCA approach. Therefore, hybrid LCA methodologies are effective at capturing full supply chain and enterprise level emissions and ensure a complete analysis across the boundaries of the systems investigated.[7]

To enhance the LCA quality, Yuan et al. addressed the temporal differences in inventory analysis data for existing LCA.[8] For example, often the emissions taking place during a product’s life are treated with the same magnitude over time. In reality, the longer the life of a product, the greater the uncertainty is that the presumed emissions will occur in future. For instance, future advances in technology such as complementary goods, or recovery techniques, may mitigate use or end of life phase emissions. In addition, policy may restrict use or disposal of products in the future which will lead to emission changes in use or end of life phases.[8]

To avoid overestimations of later emissions, Yuan et al. introduced a discount rate to represent the probability of an emissions mitigating technology being developed.[8] The effects were studied in a case study on carbon dioxide emissions on the VW Golf A4, where a 5% annual discounting rate resulted in roughly 5,500 kg or 20% less CO2 emission over the life time of the vehicle, while a 10% annual discounting rate produced a difference of 9,200 kg or nearly 35% less compared to the baseline emissions. These discrepancies between the different LCI models are useful for understanding the temporal aspects of LCA and point out further research needs.[8]

A sustainable manufacturing strategy for a company requires suitable metrics at all levels of the enterprise.[9] Selecting these metrics is challenging because it is not an inherently intuitive process. Reich-Weiser et al. developed a methodology to determine appropriate metrics that follows the ISO14040 standard.[9] In the first step of this methodology, goal definition, the company has to determine the objective for the study which broadens or narrows the scope of metrics. The next step defines the metric type from the main types "cost" or "sustainability" metrics. The third step identifies the scale of application at supply chain, factory, manufacturing line or machine tool level. The last step determines the geographic scope and finalizes the choice of effective and targeted metrics.

Ongoing research focuses on the application of LCA especially for discrete manufacturing processes.[10] Today there are still inconsistencies in depth of study, including underlying assumptions in the data and data accuracy. This occurs even within individual studies and complicates the comparison of different analyses. Therefore, guidelines for a transparent inventory analysis and impact assessment are in development.

3. Greening Products

Many mechanical, thermo-mechanical or electro-mechanical systems consume more energy in the use phase than during material extraction, production or end of life. Use-phase intensive products should be improved by reducing their mass, thermal loss, and electrical loss amongst other approaches.[4] Some examples are described in the following. Semiconductor products, and energy producing components are characterized by thermal and electrical loss in their use phase; machine tools consume energy by moving masses. Energy efficiency has been in the focus of research for a while, but more and more the focus on resource efficiency and social sustainability will be included.

3.1 Greening Electronic Products

Electronic products have become essential in daily life. However, policy and business raise questions about the environmental impact of electronic products (RoHS, WEEE).

Complementary metal oxide semiconductors (CMOS) are central device structures for digital logic. Boyd et al. analyzed the life-cycle energy for CMOS chips over 7 technology generations with a hybrid LCA model.[11] They compared energy demand and global warming potential (GWP) impacts of the life-cycle stages. Although life-cycle energy and GWP of emissions increased per wafer or die, these impacts were decreasing per unit of computational power.[11] Sensitivity analysis proved that wafer yield, line yield, and die size had the highest influence on the LCA impacts. Looking at energy in the life cycle of semiconductors the study suggested reducing energy consumption in the use phase had the greatest opportunity for improvements in environmental performance.

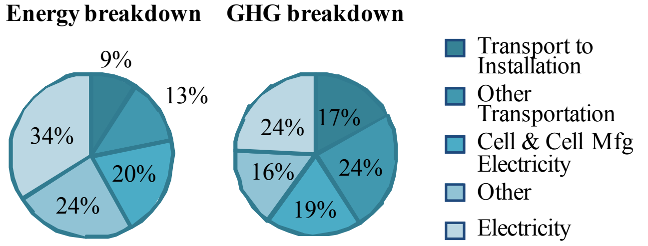

Fig. 2 Energy and GHG Breakdown for analyzed concentrator solar systems[14]

Nevertheless, the production of semiconductor products bears also potential for resource and energy efficiency. Zhang et al. did a systematic analysis of energy use in nanoscale manufacturing processes, which are especially used in semiconductor manufacturing.[12] Through a qualitative evaluation they found that imprint and plasma/ion processes had the least process requirements and therefore likewise least energy demand. In contrast, single point operations, chemical vapor deposition, Vapor-liquid-solid processes and Molecular beam epitaxy have the most requirements, i.e. likely highest energy demand.[12]

Another recent project focuses on the manufacturing of printed circuit boards (PCB) and is explained in detail in Section 4.3.

3.2 Greening Energy Producing Products

Zhang and Dornfeld set up a comprehensive framework for benchmarking the life cycle of photovoltaic systems.[13] Reich-Weiser et al. used a hybrid LCA methodology to analyze concentrator solar systems.[14] The studies showed that transportation and average electricity mix in different countries played a significant role for life cycle energy and greenhouse gas emissions. For example, photovoltaic systems have a global supply chain, so large quantities of materials may be transported very long distances via shipping and trucking.[13] A case study, in which photovoltaic systems were manufactured in Germany and installed in Spain, highlighted that this transportation accounted for 10% of the life cycle energy use of the system.[15]

In the case of concentrator solar systems, transporting the product to its final installation generated 9% of the total energy use and transporting goods within the supply chain generated 13% (Fig. 2).[14] In the greenhouse gas (GHG) breakdown, the influence of transportation on the overall GHG emissions became even larger, because the greenhouse gas intensity of the transportation modes and electricity generation was taken into account.[14]

Recent research within the Joint Center for Artificial Photosynthesis (JCAP) aims to replace fossil fuels by artificial photosynthesis generators. The design and synthesis of photoelectrochemical membrane provides one challenge.[16]

3.3 Greening Machine Tools

Noteworthy examples of use-phase intensive products are

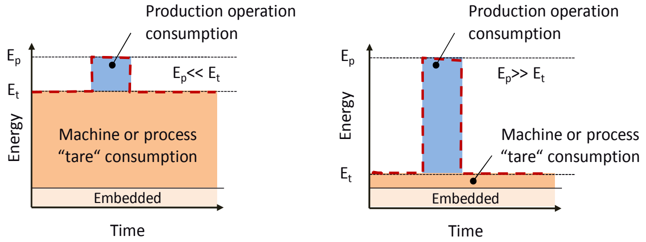

Fig. 3 Tare heavy, E_t, vs process heavy, E_p, power consumption[19]

machine tools, because their use phase is a production process of another product at the same time. Diaz et al. investigated the life-cycle energy consumption of two milling machines placed in different environments such as a job shop or commercial facility.[17] The use phase of milling machine tools comprised between 60 and 90% of CO2-equivalent emissions during the life cycle of the machine. The machine production itself can add notably to the CO2 equivalent emissions in machining of a standardized part.

The power demand of a machine tool may be divided into a constant, a variable and a processing component.[18] The constant power consumption is due to auxiliary equipment that runs independently of the material processing such as machine control, hydraulics, lighting, coolant system, etc. The variable power is consumed to keep the machine in idle state, for example by axes and spindles. It depends partially on process parameters such as spindle speed and feed rates. Both constant and variable power consumption form the "tare" energy of a machine tool.[19] The production operation power or processing power depends on the process conditions such as cutting conditions, material removal rate, and others.

Manufacturing operations can be "tare heavy" or "process heavy" which results in different strategies for energy reduction (Fig. 3).[19] Today's highly automated machine tools often fall into the tare heavy category, so reducing or saving energy is an important step towards higher sustainability. For example, kinetic energy recovery system (KERS) presents an opportunity to realize power savings. Diaz et al. modeled a KERS system on a machine tool`s spindle and achieved savings of up to 25%.[20]

Another strategy applies especially for process heavy operations and aims to reduce the process power consumption. This can be done by shortening or optimizing the materials processing operation.[21] Examples for machining, grinding and drilling processes are discussed in the following sections.

4. Greening Manufacturing Processes

4.1 Greening Machining Processes

The energy and resource efficiency of manufacturing processes can be enhanced by reducing the machine tare energy as discussed or by minimizing the process energy. The best strategy depends largely on the machine tool. Diaz et al. for example showed for a case study on a micromachining center that an increase in material removal rate to around 600% of its original value reduced the total energy consumption to less than 30% of its original value.[22] In this study surface integrity was not regarded. For larger machine tools the tare consumption would be much higher, but also higher material removal rates would be possible with less processing energy.

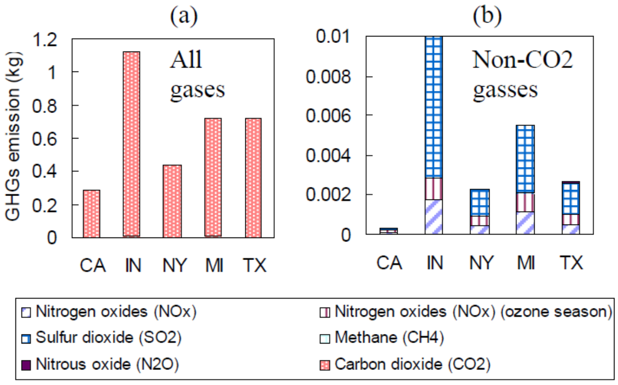

Fig. 4 GHG emissions when machining a test piece in different U.S. states[26]

In the following we elaborate the strategy to minimize process energy by machining process parameters. Previous research showed that a higher material removal rate (MRR) decreases overall energy consumption of a machine tool for the same volume of material removed.[22-24] This is true especially for tare heavy machine tools. Although the higher MRR increases the process power demand, the decrease in processing time dominates, thus reducing the total energy consumption. Diaz et al. introduced a specific energy model for machining at different material removal rates.[22] This model helps to setup an environmentally benign process with only few preliminary tests. However, the machinability of materials and specific energy are not only influenced by processing parameters, but also by the machine tool setup and cooling lubricant conditions.[25] Therefore, the specific energy model will be enlarged to work on a larger field of application.

Moreover, the energy demand cannot be estimated simply by processing time or MRR. Kong et al.[26] followed the work from Rangarajan and Dornfeld[27] on optimizing the tool path for minimum cycle time. They showed the influence of the configuration of machine axes on the energy demand and processing time. For this issue, Kong et al. suggested process analysis software tools by using web-based environment and application programming interface (API).

Fig. 4 shows that the location of production results in different values and characteristics of emissions.[26] This is because of different power sources in electricity generation. For example, in Indiana (IN), USA electricity is mostly generated by coal.[28] When the test piece is machined in Indiana the GHG emissions are four times than if it is machined in California (CA), USA, where gas, nuclear and hydro are the main sources of electricity.[26,28]

Besides these efforts on reducing energy and greenhouse gas emissions it is important to take all resource streams into account. Future research aims at reducing impacts of resource uses in addition to minimizing energy use.

4.2 Greening Grinding Processes

Abrasive processes are key technologies to produce high

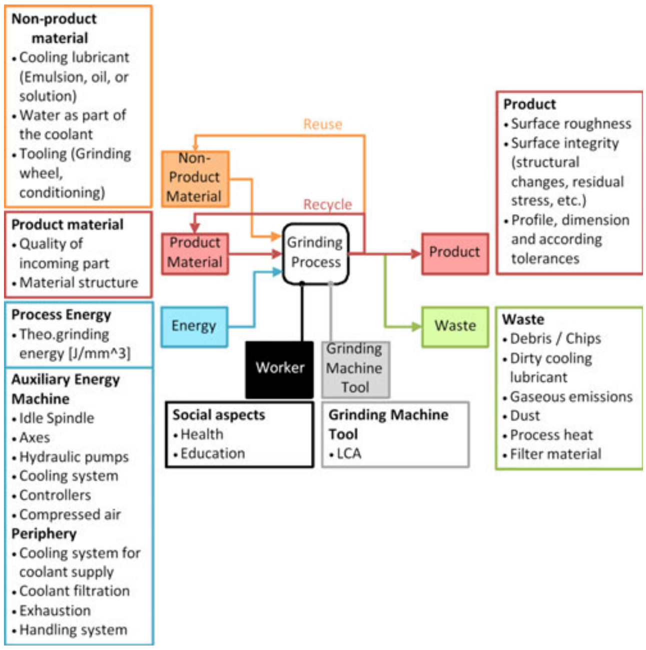

Fig. 5 Scope of LCI of a grinding process[10]

surface quality and dimensional tolerances. Surface integrity in grinding processes is generated by complex mechanisms and, therefore, grinding is hard to describe holistically.[29] A Life Cycle Inventory (LCI) for grinding helps to understand which process components and parameters affect the environmental impact (Fig. 5). The LCI describes not only the energy and material streams, but also clarifies potential levers for improving process sustainability.

Klocke et al. reviewed the grinding variant centerless grinding. Within their analysis of the process, the tools, the machines, auxiliary steps, and cooling lubricant, they found the potential to reduce impact on workers and environment.[30] Linke et al. showed the successful combination of high speed grinding and speed stroke grinding, i.e. surface grinding with high table speeds.[24] The experimental results proved that the process decreased grinding energy, grinding power and tool wear.

Abrasive tools are important but often disregarded elements of the abrasive system. Therefore, the life cycle of abrasive tools is analyzed comprehensively.[31] Tool design and tool production decides basic functions for the tool use phase including tool wear, tool life, productivity and performance.

On a larger scale, abrasive machining can enhance life and performance of the machined product within its own use.[24,32] Trade-offs are possible between higher impact in the manufacturing phase and higher product efficiency reducing the overall environmental impact.

4.3 Greening Drilling of Printed Circuit Boards

Further work on greener manufacturing processes tackles energy and resource efficiency of drilling micro-holes into Printed Circuit Boards (PCBs). Higher feed and, therefore, reduced process time lead to minimized energy, especially with the high tare machine tools involved. Enhanced productivity and reduced scrap parts are simple ways for more sustainable drilling operations as well.

The drilling burr is an intrinsic problem that also affects the process chain by adding the deburring process.[33] The cost of deburring is always substantial[34] and environmental burden can be high, so these processes should be avoided or shortened. Understanding the formation of drilling burr is especially important to predict burr dimension and to minimize burr generation.

The process conditions for different burr types were sorted by Drilling Burr Control Charts[35] providing a database for process layout and helping to understand the burr formation mechanisms. First optimized ranges of operating conditions were found.[34]

Different strategies for greening PCB drilling processes were formulated.[34] For instance, the drilling tool itself has an important influence on the burr generation by its wear behavior and geometrical design. Innovative drilling tool designs exist that require capable tool grinding processes.[36] In this case there is potential for trade-offs between sophisticated and possibly more energy consuming tool grinding and reduced environmental impact in the tool use, which is the drilling operation leading to a greener product consequently.

4.4 Greening Process Planning

Traditionally, manufacturing systems define productivity, flexibility, part quality and cost effectiveness. For example, a changeable, modular design of manufacturing systems can improve introduction time of new products and increase variability of generated products.[37]

Complex parts require several machining processes adding up to the total embedded energy of these parts. To reduce this embedded energy the process planner has to analyze different system levels, ranging from enterprise to chip formation. Widespread temporal ranges from days to microseconds go along with these levels.

Vijayaraghavan and Dornfeld developed a software tool for monitoring energy consumption across the different system levels and temporal ranges.[38] The software tool monitors idle and non-value-added periods in machining, detects process instabilities through power usage profiles, tracks maintenance states of machine tools, enables environmental reporting on per-part basis, etc. This work contributes to energy efficient decision making across multiple levels of a production system.

5. More Levels to Production Systems

According to the idea of “technology wedges” several improvements along the production system can add up to higher eco-efficiency.[3] Transportation, factory location, supply chain, and packaging are additional levels to consider besides the discussed levels of environmentally benign product use phases and manufacturing processes. Life cycle assessments of several case studies showed the high impact of transportation or electricity mixes on the product life cycle.[13,14,26]

Producers can choose suppliers within their supply chain and manufacturing locations, which affect the transportation of the components to factories and/or consumers. Different transportation modes such as air freight, rail, trucking, and inland waterway transport have particular profiles of flexibility, timeliness, security, risk, reliability, and service. Additionally, different green house gas emissions and energy consumption per mass transported per distance occur.[39]

The manufacturing location influences not only the distances traveled and possible transportation modes, but moreover the environmental impact of the factory.[14,26,39] Especially the greenhouse gas intensity varies with the electricity mix at different locations associated with different electricity sources. The mix not only varies per country but also per region.

However, the approach to consideration of the electricity generation can be debated. Often, the more straightforward quantity, energy, is preferred to green house gas emissions, but it does not allow for a true understanding of greenhouse gas emissions.[9] In contrast, most approaches neglect other metrics in electricity generation like risk due to radioactivity and impacts from mining of radioactive components.

Other environmental impact factors in manufacturing location or supply chain choice are energy scarcity, energy independence, scarcity of non-renewable resources, water availability, and others.[9] Reich-Weiser and Dornfeld focused on the two measures of water scarcity and greenhouse gas emission.[40] On the one hand, these measures are important to climate change concerns; on the other hand they have different impacts across supply chain decisions.[40] Greenhouse gas emissions have a global impact which is not affected by emission location. In contrast, water scarcity is a local measure and predicts the long-term sustainability of a manufacturing location.[40] Zhang and Dornfeld even addressed the controversial aspect of energy use per worker hour as possible metric.[41] In future, more social sustainability aspects will be implemented in supply chain considerations and LCA in general.

For the past several years, packaging has been one element of LMAS research. Packaging spans across the supply chain of nearly all products. It is important for marketing and product image, but also protects the product during transport.[42] Choosing sustainable packaging is highly complex and needs multiple metrics. The challenges are shown by benchmarking current packaging options for daily use products.[42]

6. Leveraging

The view of the total product life cycle exceeds the boundaries of the enterprise and supply chain level. Even with a higher energy or resource demand for enhanced production, improved product performance can offset the higher production efforts with reduced environmental burden in the use phase. This concept is called “leveraging manufacturing”.[5] One example for leveraging precision manufacturing was obtained in a gear grinding process.[32] Higher efforts in producing higher surface quality resulted in higher mesh efficiency of a gear pair. As a consequence, the entire drive train consumed significantly less energy in its whole use phase.[32]

In conclusion, it is important to regard manufacturing processes not only as obligatory steps to generate a product, but moreover to consider technology as an enabler for more environmentally benign products. Dornfeld points out that manufacturing-driven improvements are indeed responsible for substantial environmental impact reductions.[5]

7. Conclusions

With the growing environmental consciousness, manufacturers are taking increased responsibility for their products. Therefore, they have to understand the complete life cycle of their products. Life Cycle Assessment methods are useful tools to analyze products and processes. However, there are ongoing improvements of the methods and metrics, also addressing transparency of life cycle analyses and social sustainability. The temporal discrepancies of LCA need to be investigated further, especially for products with a long life time.

Different examples for improving products were discussed, but ongoing work broadens the number of applications and will emphasize resource efficiency in addition to energy efficiency. The use phase of semiconductors bears great potential for higher eco-efficiency. Another important research area for higher sustainability is to save energy in the idle state of machine tools. New research even focuses on an emerging energy technology by replacing fossil fuels by artificial photosynthesis generators.

In addition, the environmental impact of manufacturing can be enhanced, e.g. by greener processes, greener production systems, or greener supply chains. This review forms the foundation to understand actual achievements and to define future research directions. For example the energy efficiency of nanoscale manufacturing processes and strategies for greening PCB production need more research. Existing machining models for specific energy or power should be enhanced by incorporating more processing parameters, the machine tool setup and cooling lubricant conditions to enable an environmentally benign process setup. The life cycle of tools, e.g. cutting tools, abrasive tools, dies and molds, needs more research.

Future work will touch multiple aspects to provide sustainability wedges that add up to a larger gain in higher sustainability. Research has to take all resource streams into account, not only energy and GHG emissions. Embodied energy has to be included into manufacturing planning and monitoring and into supply chain considerations. Moreover, social sustainability will be more and more important for life cycle analyses.

The broadest view on production systems is leveraging manufacturing, which can facilitate greater sustainability for use-phase intensive products, but needs more emphasis. Manufacturing has the potential to achieve substantial reductions of environmental impact.

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For more information on the research activities of the LMAS, please visit http://lmas.berkeley.edu.

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