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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 besides the common economic view. 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. The research includes approaches to enhance Life Cycle Assessment Methods, understand the life cycle of different products, improve manufacturing processes and make use of higher levels like leveraging or supply chain decisions. These approaches support sustainable production practices.

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NOMENCLATURE

API = Application programming interface
CMOS = Complementary metal oxide semiconductor
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. As a result, companies are focusing increasingly on the ecological impacts of manufacturing processes besides the established economic view.

Haapala et al. gave a comprehensive review on research in sustainable manufacturing [1]. 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 of these needs and is described in this paper. Single improvements can be regarded as “technology wedges” which add up to sustainable technology [2].

2. Where to Focus on - Products or Manufacturing Processes?

The product life cycle consists of raw material extraction, production, use and end of life. The ecological impact of these phases often differs depending on the product. Producers have to identify which phases they will direct their efforts 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, the manufacturing process, machine or system [3, 4].

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.

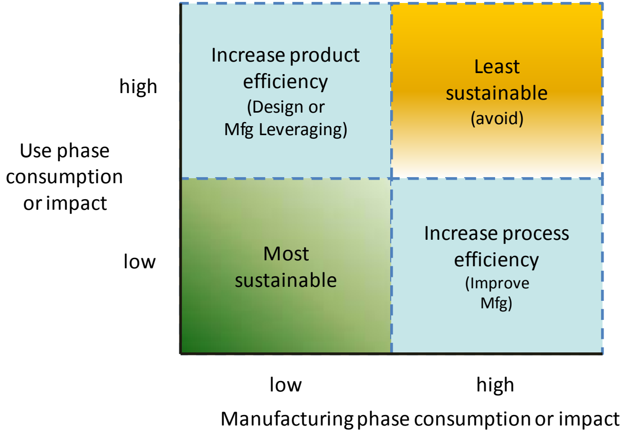

Fig. 1 Impacts in manufacturing vs use phase [3]

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 [5]. 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.

To help with the wide range of LCA methods, Reich-Weiser et al. discussed the differences between frameworks and sorted them into different spatial and temporal levels of complexity [5]. Hybrid LCA methodologies were found to be effective at capturing full supply chain and enterprise level emissions; however, trade-offs at the factory or machine tool level are best analyzed by process LCA approaches [5].

To enhance the LCA quality, Yuan et al. addressed the temporal differences in inventory analysis data for existing LCA [6]. For example, the emissions taking place during a product's life are treated with the same magnitude over time. To avoid overestimations of later emissions, this study introduced a discount rate to represent the probability of an emissions mitigating technology being developed.

A sustainable manufacturing strategy for a company requires suitable metrics at all levels of the enterprise [7]. 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 [7]. 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 [8]. 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 [9]. 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.

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 [10]. 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 [10]. 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.

However, there are other opportunities to green electronic products. For example, the production of semiconductor products includes potential for resource and energy efficiency, too. Zhang et al. did a systematic analysis of energy use in nanoscale manufacturing processes, especially used in semiconductor manufacturing [11]. 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 [12]. Reich-Weiser et al. used a hybrid LCA methodology to analyze concentrator solar systems [13]. Both studies showed that transportation and average electricity mix in different countries played a significant role for life cycle energy and greenhouse gas emissions. The resulting relevance of plant location and supply chain decisions will be developed in section 5.

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 [14].

3.3 Greening Machine Tools

Noteworthy examples of use-phase intensive products are 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 [15]. The use phase of milling machine tools comprised between 60 and 90% of CO2-equivalent emissions during the life cycle of the machine. However, the machine production 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 [16]. 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 [17]. 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. 2) [17]. 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% [18].

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 [19]. Examples for cutting, grinding and drilling processes are discussed in the following sections.

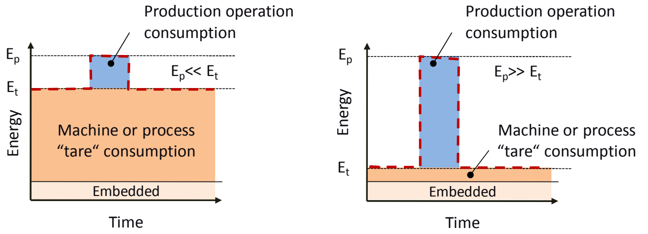

Fig. 2 Tare heavy, E_t, vs process heavy, E_p, power consumption [17]

4. Greening Manufacturing Processes

4.1 Greening Cutting 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 latter is related to the machining process parameters as elaborated in the following.

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 [20, 21, 22]. 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 [21]. This model helps to setup an environmentally benign process with only few preliminary tests.

However, the energy demand cannot be estimated simply by processing time or MRR. Kong et al. [23] followed the work from Rangarajan and Dornfeld [24] 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). As in [13], the location of production resulted in different values and characteristics of emissions.

4.2 Greening Grinding Processes

Abrasive processes are key technologies to produce high surface quality and dimensional tolerances. A Life Cycle Inventory (LCI) for grinding helps to understand which process components and parameters affect the environmental impact (Fig. 3). 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 [25]. Linke et al. showed the successful combination of high speed grinding and speed stroke grinding, i.e. surface grinding with high table speeds [22]. 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 [26]. 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 [22, 27]. Trade-offs are possible between higher effort in the manufacturing phase and higher product efficiency reducing the overall environmental impact.

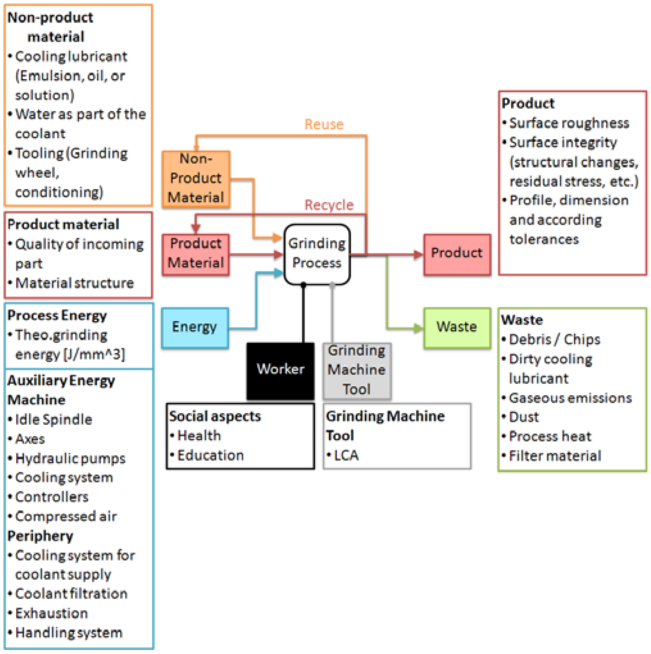

Fig. 3 LCI of a grinding process [8]

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. Therefore, the formation of drilling burrs is investigated in particular. The process conditions for different burr types are sorted by Drilling Burr Control Charts [28] providing a database for process layout and helping to understand the burr formation mechanisms. 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. 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

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 [29]. 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 [2]. 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.

Producers can choose suppliers 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 [30].

The manufacturing location influences not only the distances traveled and possible transportation modes, but moreover the environmental impact of the factory [13, 23, 30]. 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 [7]. 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 are energy scarcity, energy independence, scarcity of non-renewable resources, water availability, and others [7]. In [31] Reich-Weiser and Dornfeld focused on the two measures of water scarcity and greenhouse gas emission. On the one hand, these measures are important to climate change concerns; on the other hand they have different impacts across supply chain decisions [31]. 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 [31]. Zhang and Dornfeld even addressed the controversial aspect of energy use per worker hour as possible metric [32].

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 [33]. Choosing sustainable packaging is highly complex and needs multiple metrics. The challenges are shown by benchmarking current packaging options for daily use products [33].

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 production costs with much higher reductions in the use phase. This concept is called “leveraging manufacturing” [3]. One example for leveraging precision manufacturing was obtained in a gear grinding process [27]. 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 [27].

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 [3].

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. Different examples for improving products were discussed.

Moreover, products can be improved in their environmental impact during manufacturing, e.g. by greener processes, production systems, or supply chains. The broadest view on production systems is leveraging manufacturing which can succeed in higher sustainability for use-phase intensive products.

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

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