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Assessment of energetic leverage effect using a virtual prototype

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Abstract

The so-called energetic leverage effect describes the influence of manufacturing strategies on the energy balance in the use-phase of tribological components in technical products. The objective of the presented approach is to consider this effect in early phases of product engineering of construction and agriculture machinery with the help of a prospective life-cycle-assessment.
In the approach a virtual prototype is developed. This enables a quantitative assessment of the use-phase of a product in early product development phase. The virtual prototype simulates the behavior of considered components, in this case gear wheels, and the effect on the energy consumption of the whole machine in its use-phase. In different simulation runs gear wheels with differences in surface quality, tribological characteristics but also in energy consumption during their production-phase resulting from different manufacturing strategies are compared. The life-cycle-assessment ensures that energy consumption of all life cycle phases is included and optimized.

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1. Introduction

The issue of sustainability is a key element in the strategy of manufacturing companies. Besides ecological and social aspects, economic aspects are contributing to this fact. In addition to the responsibility for future generations, the rising raw material and energy consumption can be mentioned as motivation for companies to include eco-efficiency aspects in their objectives. Environmental legislation is a further argument to care about energy efficiency and material input of a product.

Costumer awareness is also rising. For construction and agriculture machinery the users are interested in energy efficiency during use phase not only for economic reasons but also because of end consumers demanding environmentally benign products. Especially in agriculture where food and consumables are produced consumers are more and more sensitive to sustainability aspects, starting with health, quality and environmental protection. In the construction sector too, a trend to sustainability can be observed, as regulations for buildings are getting stricter and energy consumption of buildings is discussed. Hence, rising challenges about eco-efficiency for companies producing construction and agriculture machinery are expected.

For machinery the use phase is often considered the most important life cycle phase regarding environmental impact. But decisions about the environmental impact are determined in the design of the product. In this context, machine building companies have to ensure they consider the whole life cycle of their product, both in early product design and in manufacturing planning.

Therefore, the objective of the presented approach is to develop a tool for manufacturers to easily evaluate the impact of their manufacturing decisions across the whole life cycle of the final product. The paper discusses requirements and possible solutions for an approach of a prospective life cycle assessment (pLCA) in this context. To become prospective the LCA has to evaluate the use phase of a complex product during the early phase of product design. This is achieved by

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comparing different design specifications of subsystems and subsystem parts in a simulation approach using a virtual prototype of the complex final product. With the virtual prototype, the use phase will be simulated.

A case study of some part or subassembly for which an energetic leverage effect is expected serves as a validation of the concept. Therefore, the effect of surface quality of gear wheels incorporated in an excavator was identified. The differences in surface quality result from different manufacturing strategies like milling with or without grinding afterwards. Since the paper is focused on the modelling of the energetic leverage effect between manufacturing and use phase, other phases in life cycle as well as other environmental burden beside energy consumption are not considered in the paper.

The approach is divided in two steps representing the two life cycle phases that are in the focus: manufacturing phase of tribological parts of the final product (e.g. gear wheels) and use phase of the complex final product (e.g. drive train of a commercial vehicle). For both phases the energy consumption has to be calculated depending on different manufacturing strategies. After an overview of related work and the identified research gap, the general approach, concepts to determine energy consumption in the use phase and the concept for a virtual prototype that can be used in pLCA are described.

2. Related work

The contribution of a company to a sustainable development can either be directly by reducing the environmental impact of its production system or indirectly by reducing the impact of the product during its use. Therefore, trade-offs between such direct and indirect effects need to be considered carefully to avoid suboptimal decisions [1].

This is especially true for energy consuming products as e.g., automobiles [2] or machine tools [3]. Although little attention has been given to commercial vehicles compared to passenger cars, the same can be stated for construction and agriculture machines [4,5]. Their environmental impact is usually considered biggest in use phase. But to a large extent this impact is determined during design and manufacturing phase.

This is why product development has to include a life-cycle perspective of the product. It is important to analyze life cycle impacts of a product in the early phases of product development or even before to identify hot spots and focus on the highest impact on the life cycle [6]. Similar to the frontloading of costs (i.e. costs of product production and/or use is determined during product design [7]) the environmental impact is most easily reduced as long as the product is still in the design stage [8].

For complex products like construction machinery not only the design of the final product but also manufacturing strategies for components and subassemblies have to be considered. The influence of manufacturing strategies on the environmental performance of the final product while used is important since small additional efforts in manufacturing pay off through huge improvements of the environmental performance of the final product. Dornfeld et al. call this a leverage effect [9].

In many cases, components in tribological systems have a large impact on the sustainability of the final product [10]. For selected components a higher use of energy and thereby rising costs in production pay off with an energy-saving product in the use phase. This energy saving is directly linked e.g. to the quality of the manufactured surfaces or to tightened production tolerances [9]. Improved surface quality of the generator bearing by grinding can be mentioned as an example of how efficiency of wind turbines or combustion engines can be improved [10]. Weight reduction resulting from smaller machining tolerances are of great interest in vehicles and even more in aircraft construction [9].

Helu et al. [11] investigate the relationship between precision and life cycle environmental impacts to evaluate the impact of manufacturing process precision on the functional performance of a product during its use phase. It shows in the case of automotive drive train components, that high precision in manufacturing has an impact on entire life cycle. However, it is emphasized that the examination was quite broad and may not be suitable for every product.

Existing case studies on life-cycle assessment of complex products consider the use-phase and the manufacturing phase. But especially for complex products the influence on the manufacturing of single components is often neglected [2,12]. Single components are only considered as material input and only their impact from material extraction and material transformation is included by using LCA-databases. To improve knowledge and databases on unit processes in manufacturing a lot of research is ongoing [13,14]. Especially energy consumption of different manufacturing technologies is examined [15,16] to enable the assessment of the manufacturing phase in more detail. Though, it is still very difficult to include all the influencing factors on product, process and machine level in manufacturing like cutting speed, material composition, tool, work piece design, and production environment [17].

Furthermore, the environmental impact of a product during its use phase is difficult to evaluate since using conditions are variable. It depends on many factors that are unknown to the producer or differ for the specific units of the product. For machine tools for example, Diaz-Elsayed et al. observed that it is important to comprise the production environment where it is used into the LCA [3]. Since the size of the factory determines the load factors of the machine and the location of the factory the transport routes, these are important factors to include into the analysis.

For the suppliers of different parts or subassemblies within a machine or any other complex product it is even harder to evaluate the use-phase of their product, and therefore to decide about manufacturing processes.

Here, the concept of virtual prototyping provides interesting possibilities. Virtual prototyping is an upcoming technique to cope with multiple alternatives during design stage of a product [18]. The big advantage of a virtual prototype beside proof testing before assembly is the possibility to explore new design possibilities and analyze their functionality [19]. Virtual prototyping is used to validate