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Measures for Energy-Efficient Process Chains

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Abstract

Energy efficiency is an essential factor for promoting sustainable manufacturing. Various types of energy consumption occur in modern process chains. This includes usage of electrical energy, e.g. for machine tools or air compression, but also energy consumption through use of resources (such as raw materials and supplies). In this paper, a process chain from the automotive industry is considered with the purpose of identifying energy saving potentials of various kinds. The process chain is used for the production of an axle component. In order to evaluate saving potentials, the current state of the process chain is analyzed. Then, the impact of process parameter optimization on the energy demand is examined. It was found that small energy savings through parameter optimization are possible. However, this can be problematic since process parameters are closely linked to process reliability, so energy savings might be achieved at the expense of product quality. Furthermore, it turns out that the reduction of the process energy is not sufficient for a broad energetic optimization of the process chain and base load reducing measures are required instead. Therefore, further analysis is focused on energetic effects of such measures as machine design, recycling, adjustments of process chain and product design. These were found to be an effective lever for minimizing energy demand of the process chain. A combination of feasible measures adds up to a potential energy saving of 11.5% in the investigated scenario.

Keywords: energy optimization, process chain, detailed planning, production control, CED

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1. Introduction

Scientific findings on the effects of industrial production on the consumption of energy and natural resources and the resulting climatic consequences are currently receiving more and more attention. Additionally, the increased sensitivity of the society to environmental issues makes it necessary to take greater account of this topic in industrial production.

Energy demand during production processes directly influences the environmental impact of a product. However, the environmental footprint can be affected by upstream phases (e. g. production of used raw material) and downstream phases of a product (e. g. use phase). Energy efficiency in the production of raw material has a direct effect on the environmental impact of produced parts. Apart from this, weight reduction can contribute to a reduced energy demand during the use phase in the case of automotive applications [1].

This paper discusses various kinds of energy saving potentials for an exemplary process chain containing machining processes.

First, an optimization approach to reduce the energy demand of the process chain during production is presented and evaluated. Subsequently, additional approaches addressing the production as well as upstream and downstream phases are described. The resulting energetic saving potentials are then applied to the process chain and the findings are discussed.

2. State of the art

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2.1 Energy consumption in machining processes

Within the manufacturing industry, machining is an important technology due to the achievable precision, quality and flexibility [2]. A significant share of the environmental impact of this technology and its processes (such as milling, turning and drilling) is determined by electric energy consumption [3]. Even small measures to improve the energy efficiency of a machine tool can lead to high savings over its life cycle due to its widespread use [4].

Nonetheless, not only the machining process itself affects the energy consumption of machine tools. Rather, a considerable proportion of the energy required is needed for peripheral processes [2]. Figure 1 gives an overview of the distribution of energy consumption during an exemplary milling process.

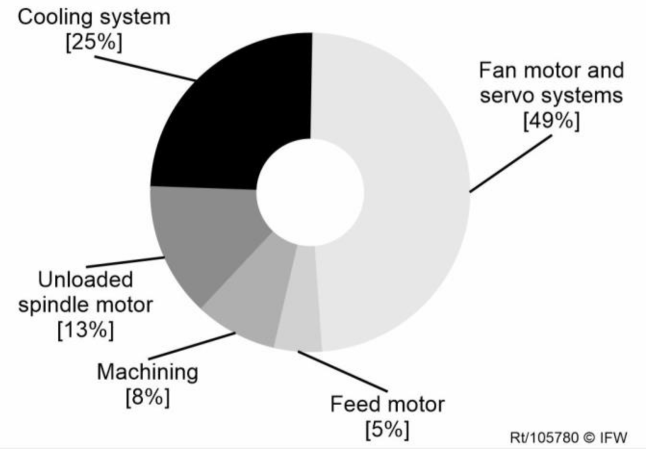

Figure 1: Energy consumption during a milling process [5]

In this case, the actual machining process is responsible for only 8% of the total energy consumption. Hence, other consumptions account for 92% of total energy demand. Other authors quantify the share of peripheral systems in the total energy consumption of a machine tool at 75% [6] or 85% [7].

Thus, it can be concluded that a comprehensive view of the manufacturing process is necessary to identify and implement energy-efficient measures.

A renowned indicator describing processes as a whole in terms of energy is the Cumulative Energy Demand (CED) [8]. This approach has been proven suitable for evaluating production processes by a multitude of authors [9, 10, 11]. Based on the CED an approach for the energy-focused assessment of machining processes was developed [12], which forms the mathematical basis for the present research and will be briefly described in the following.

The CED considers the total energy demand beginning with the production of the raw material to further processing up to the disposal of the product [13]. In the context of this work the CED of a single process is calculated according to formular 1:

$$CED = E_M + E_{CL} + E_T + E_A \tag{1}$$

With E_M beeing the machine-related energy demand and E_{CL} beeing the energy consumption of the cooling lubricant. The energy demand regarding to the tool is represented by E_T . Lastly, E_A completes the CED as the energy consumption of other aggregates e.g. conveyor belts.

2.2 Prediction and optimization of energy consumption in machining process chains

While the energy demand of machining operations depends on multiple factors like machine characteristics, process parameters influence the variable share of energy consumption directly [14]. Cutting speed, feed rate and depth of cut can therefore be optimized with regard to minimal energy demand of a machining process. Different approaches have been proposed to carry this out. This includes the use of various algorithms like response surface methodology [15] or metaheuristics (e. g. particle swarm optimization [16]). However, these approaches consider electric energy demand of the machine tool, but leave out indirect energy consumption by tool wear or usage of cooling lubricant that can have a relevant influence on the environmental impact of machining processes. Moreover, the focus is on single processes rather than process chains.

CED of process chains can be described as:

$$CED_{PC} = (1 + SR) \sum_{j=1}^{m} \left(\sum_{i=1}^{n} CED_{i,j} + \sum_{i=1}^{n} E_{I,i,j} \right) \tag{2}$$

CED of single processes (s. Eq. 2) are summarized in the term $CED_{i,j}$. Machine idle time ($E_{I,i,j}$) and scrap rate (SR) influence the CED of a process chain. These factors are considered through terms $E_{I,i,j}$ and SR. The term CED_{PC} indicates the energy demand of an entire process chain. A detailed description of this approach is given in [12].

3. Case-Study

Within the present study, a real process chain to produce a part of an axle is considered. The component is made of a steel grade similar to C55E (1.1203). The application of the methodology described in chapter 2.2 to this process chain is displayed in this chapter.

3.1 Case study: Considered process chain

The process chain is depicted in Figure 2. It consists of four machining processes, a mechanical forming process as well as heat treatment of the machined part.

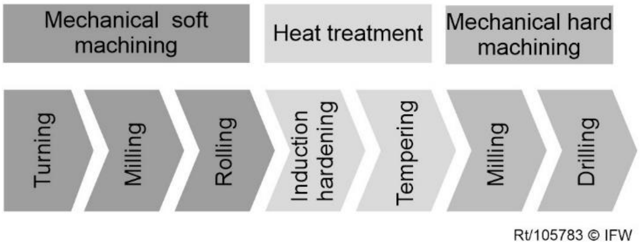

Figure 2: Schematic representation of the investigated process chain

The considered types of energy consumption are electric energy (machine and aggregates) and indirect energy consumption by tool wear as well as usage of cooling lubricant (only in rolling process) and water.

Figure 3 shows the current status of energy consumption in the respective process chain for a manufactured part. To be able to compare the effects of energy saving measures, the energy of the respective processes was measured per component by connecting a power meter to the machines. Further peripheral influences on the energy consumption of the process chain were determined using Eq. 1. In addition to direct energy consumption, energy consumption of raw materials and supplies is also calculated here. For the calculation of the energy demand through the use of raw material, a recycling rate of 47% is considered, which corresponds to the share of recycled material in steel production in Germany [17].

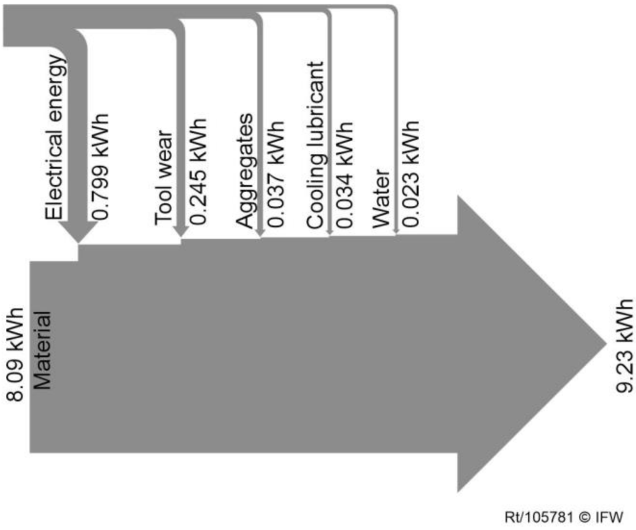

Figure 3: Environmental evaluation of considered process chain

It becomes clear that a large part of the overall energy demand for a manufactured part relates to the extraction of raw material. While electric energy consumption by machines and aggregates (supply of compressed air) is a significant factor, indirect energy consumption by tool wear and usage of cooling lubricant and water makes up a small proportion of the overall energy demand.

In the following, an approach for optimizing cutting speed and feed rate of all machining processes is described.

3.2 Optimization approach

As discussed in section 2, an approach that considers direct as well as indirect energy consumption of entire process chains is needed. Therefore, an approach is proposed that combines the CED of process chains with an optimization algorithm.

The objective function is represented by the CED of the considered process chain (Eq. 2). By using this approach, indirect energy consumption (e. g. through tool wear) is considered. Additionally, varying process durations and resulting idle times of subsequent processes are included.

Due to its comparibly short calculation time, a simulated annealing algorithm is used to perform optimization of the process parameters for all machining processes. The used algorithm is described in [18]. Efficient parameters for the optimization algorithm are also based on the publication mentioned (Table 1).

Table 1: Parameters for optimization algorithm

Parameter	Value
N (maximum iterations)	1,000
q_v (Parameter for visiting distribution)	2.62
T (initial temperature)	5,000 K

Cutting speed and feed rate of all machining processes of the considered process chain are passed to the optimization algorithm. These variables are optimized in order to reach the minimal CED of the whole process chain.

3.3 Results

The obtained results indicate that setting the maximum possible values for cutting speed and feed rate for every machining process leads to the minimal overall energy demand of the process chain. It stands to reason that this is due to the high base load of machines and aggregates relative to the variable load of machines.

This effect is not neutralized by higher indirect energy consumption due to rising tool wear. Changing idle times caused by machines waiting for longer lasting processes also do not counteract the effect. The CED including direct and indirect energy consumption for one representative process (turning) of the process chain is shown in Figure 4. A common range of process parameter values for the considered material is displayed with the expected CED. The grayscales indicate the level of the CED.

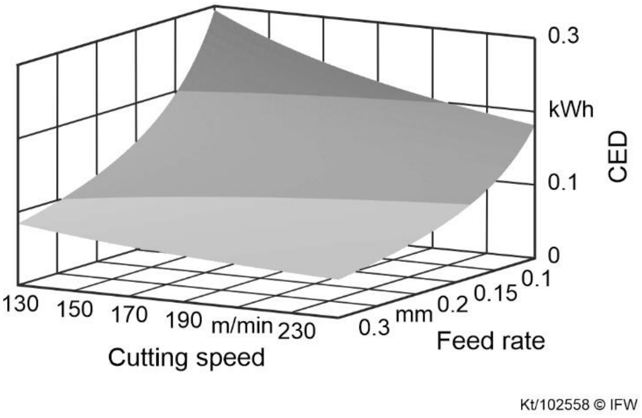

Figure 4: CED of turning process

It is apparent that with rising values of cutting speed and feed rate, the potential for energy savings decreases. The increase of process parameter values is limited by a number of factors. High values for feed rate might affect the final surface quality of manufactured parts [19]. For processes that do not influence the final surface of a manufactured part, limitations regarding maximum feed rate values can arise due to acceptable surface conditions for downstream processes.

The results show the overall tendency that in consideration of process stability and workpiece quality, short process times lead to an energy efficient process chain. A reduction of the process time must however be coordinated across the entire process chain. Otherwise idle state of machines might occur, which leads to reduced energy savings.

These findings encourage the importance of alternative approaches to advance energy efficiency in process chains that include machining operations.

4 Further levers for energy optimization

The attempt to minimize the CED of a process chain described in 3.3 showed a relatively small potential to lower the energy demand. Consequently, three promising further levers for energy optimisation from the literature are applied to the considered process chain in order to allow an impact assessment.

4.1 Machine design

Some authors have already discussed that the properties of a machine tool have a decisive influence on the energy consumption of the process step [20, 21, 22, 23]. As part of a literature research, the following measures including their impact on energy consumptions have been identified (Table 2).

Table 2: Selected energy savings measures

Measures	Description
1. Design improvements [24, 4]	One way to reduce the energy consumption of machine tools is to make design improvements, such as the use of direct drives or the optimization of power transmission. Here, a reduction of the total energy consumption of a machine tool by up to 27% is possible.
2. Standby-measures [25]	Machine tools usually have a high base load, which leads to a corresponding energy consumption. By using the stand-by mode during downtime, the energy consumption of a plant could be reduced by 23%.
3. Twin production [26]	Twin production in this context means simultaneous parallel machining with several spindles. This can significantly reduce the total machining time required to produce the same output. Theoretically, a reduced energy requirement of up to 60% can be achieved, however, this measure depends heavily on the machine used and the machining process.
4. Oversizing of machine tools [21, 24]	Planning of a manufacturing process is usually done under uncertainty. If a machine tool is oversized according to its actual use, a higher energy requirement is the result due to the higher base load. In the literature, a reduction of the energy consumption by 10% is proven, provided that oversizing can be avoided.

The previous approaches to optimizing the energy consumption of machine tools were considered to be the most effective in relation to the present case study.

Figure 5 illustrates the savings potential of three approaches with the biggest impact on base load (design improvements, standby measures and oversizing) for the considered process chain.

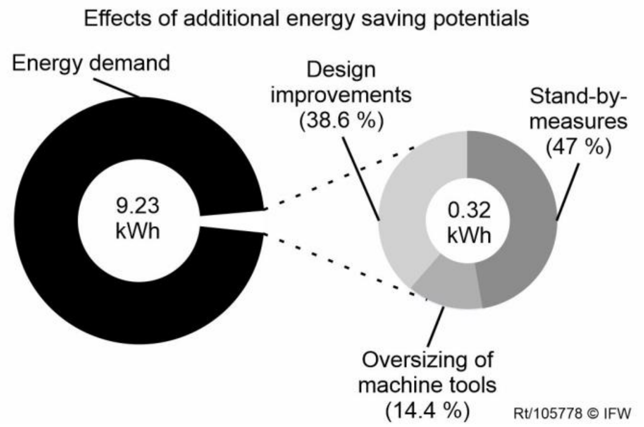

Figure 5: Effects of additional energy saving potentials

In summary, it can be stated that a consideration of the machine tool design within the process chain planning phase is energetically relevant. The purchase of machine tools has to be planned carefully to avoid oversizing, which would lead to higher energy consumption. Later energy measures can only be achieved at great expense. All in all, the result is an energy saving of more than 3.5% of the total energy consumption of the present process chain. These savings can be achieved with comparatively small effort, since the process chain itself does not have to be adjusted.

4.2 Recycling

When applying the CED in order to evaluate the environmental impact of a product, the material can have a significant impact on the result. In the considered process chain, the recycling rate of the used workpiece material has the potential to lower the CED by a greater margin than the previously discussed measures.

While it is difficult to specify exact values for the energy demand of steel production (values differ for different steel types, time periods, regions and used processes), general reference values exist. Current values are in the range of 4.9 - 5.6 kWh per kg steel [8, 27]. Information about energy demand of steel recycling is limited, available values are in the range of 2.5 - 3.5 kWh per kg steel [28].

Figure 6 shows the CED of a produced part for different recycling rates. The used values include an added reference value [7] for the forging process to take into account that the used blanks are delivered in forged condition by the supplier. Possible calculation errors due to the range of values for energy demand of steel production are displayed. The current recycling rate (47%) is indicated by the vertical line. While the CED is 9.23 kWh at the current recycling rate, a recycling rate of 60% during steel production would lower this value to 8.7 kWh.

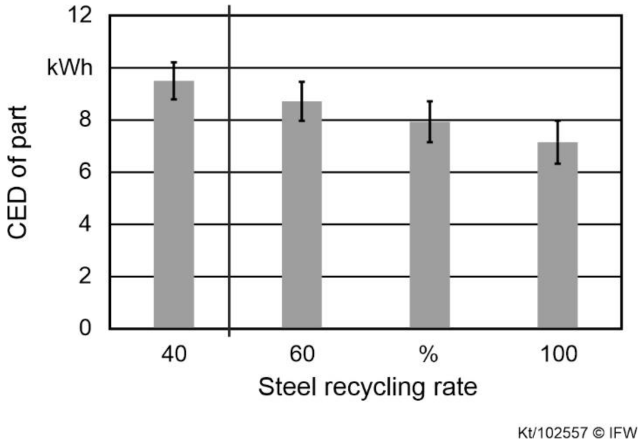

Figure 6: Influence of material recycling rate on CED

It should be noted that this measure can only be approached in the overall industrial context. Production companies cannot directly influence the share of material that is produced by recycling. However, companies can consider the recyclability of products in the design phase. High recyclability of products can lead to a smaller amount of needed primary produced material and hereby to a smaller average energy demand during material production.

4.3 Production and use phase

A key factor in optimizing energy consumption is the efficient use of resources [11]. On the one hand, primary energy, which would be necessary for the production of the raw material, can be saved [29]. Feasible adjustments to the process chain are the omission of one milling process (hard machining) and the hardening process in certain sections of the workpiece. As compensation for this, a rolling process is added to the process chain. The described adjustments along the process chain correspond to energy savings of 0.232 kWh/part (milling and hardening processes). The additional rolling process reduces the total energy saving to 0.207 kWh/part. The following assumptions were made (Table 3:):

Table 3:: Assumptions

Parameter	Value
Energy savings of process chain adjustments (assumed):	0.207 kWh/part
Parts per vehicle:	2
Energy demand per kg vehicle mass (assumed):	0.000047 kWh/kg/km
Annual vehicle mileage [30]:	13.727 km/year
Lifetime of the vehicle [31]:	18 years
CED of raw material [8,27,28,17]:	4.43 kWh/kg

As an alternative to adjustments of the process chain to manufacture a part, reduced weight of vehicles leads to lower energy requirements in the use phase [32]. At this point, the aim is to compare the energetic effects of small weight reductions in the use phase with the described adjustments to the process chain. The reduction in component weight has two consequences. Firstly, primary energy for the production of the raw material can be saved. Secondly, less energy is emitted in the use phase. Thus, a reduction in component weight has energetically a high saving potential. The foundation for an energy-efficient product can already be laid in the product development phase. To illustrate the setting lever, Figure 7 compares the effects of these two measures with the previously described energy savings achieved by adjusting the process chain. With the help of the assumptions in Table 3:, a kind of break-even point can be determined.

This emphasizes the importance of energy saving over the entire life cycle. Even a weight reduction of 0.0045 kg leads to equivalent energy savings over the entire life cycle of the car as compared to a single saving of 0.207 kWh per part by adjusting the manufacturing process chain.

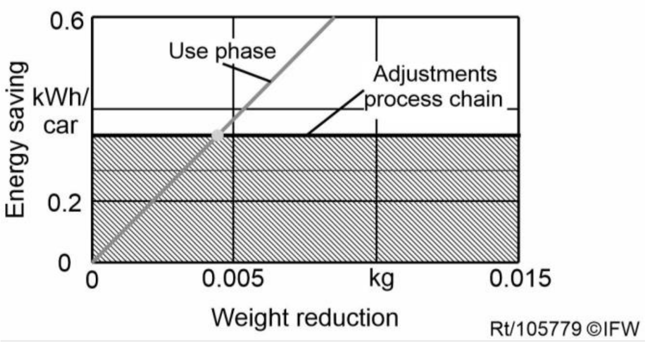

Figure 7: Comparison of the effects of energy optimization in the process chain and through weight reduction

Thus, the aspect of downsizing represents an effective alternative to the adjustment of the process chain. However, it has to be stated that energy savings by adjusting the product design come at the expense of high organisational effort.

5 Conclusion

The responsible use of resources and energy is more important than ever. However, as shown in Figure 3, the potential for savings is limited, since about 87% of the energy consumed by a manufactured part is contained in the production of used raw material. In the context of this paper a comparison between production-oriented energy optimization and other levers was made. These aim at the reduction of the material used, the relevance of an optimal machine design and the effects of using recycled material. Within the scope of this study, the other levers were examined, since it could be shown that the production-oriented optimization offers only a limited savings potential (e. g., due to the high base load).

The results of these three different approaches indicate the importance of downstream and upstream processes when optimizing a process chain energetically. For the considered use case, even a small reduction in the amount of raw material used can have a significant impact on energy

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consumption in the later use phase. In the present use case, energy savings in the use phase increase with every kilometer driven. Moreover, an additional energy saving through adjusted machine design was pointed out. Finally, the use of recycled material has a significant impact on energy savings. The primary energy input can be reduced by higher recycling rates in the production of raw material, resulting in a reduction in energy requirements in the upstream process steps of the actual process chain. A combination of the presented measures results in a potential energy saving of 11.5% compared to the current state of the process chain.

Future research topics are the development of an automated energy monitoring system for process chains based on the readout of axis and spindle currents of the respective machine tool to monitor the effect of base load reducing measures. Furthermore, the recycling of energy-intensive materials has turned out as an enormous lever to increase the energy efficiency along an entire process chain. High recycling rates of such materials will be examined.

Acknowledgements

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