Assessment of Energy and Resource Consumption of Processes and Process Chains within the Automotive Sector

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Abstract

Within this paper a methodology for the assessment of energy and resource consumption within manufacturing processes is described and two case studies from the automotive sector were evaluated. On basis of the Life Cycle Assessment approach the energy and material flows within single manufacturing processes were acquired concerning the two selected case studies. With the generated knowledge about energy and material use it was possible to show up optimisation potentials for the reduction of the ecological impact of the determined products within the manufacturing phase. The work shown in the paper was conducted within the project BEAT which is kindly financed by the Federal Ministry of Education and Research in Germany (BMBF).

Keywords:

Manufacturing Process Evaluation and Characterisation; Total Process Efficiency; Sustainability

1 INTRODUCTION

Due to the scarcity of resources and the increasing global demand to use these resources for products and power generation, the commodity prices on the international energy and commodity market are increasing heavily as shown in Figure 1. Although the prices on the markets crushed during the last world economic crisis, as highlighted in grey in Figure 1, they are constantly growing again. This vast increase in prices emerges to one of the central problems which manufacturing industry has to face [1][2].

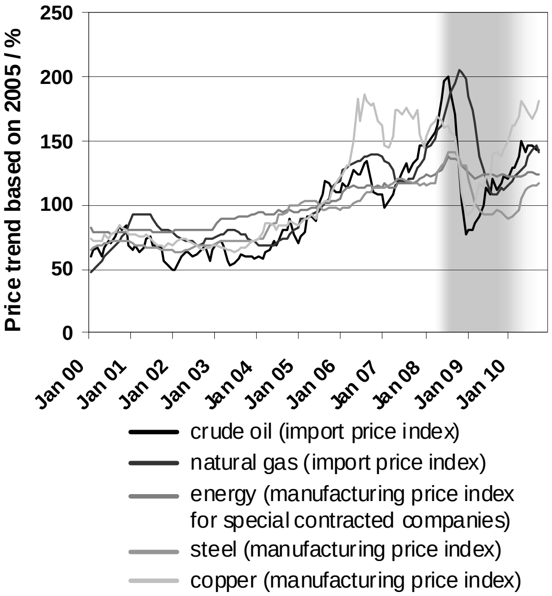

Figure 1: Development of energy and commodity prices.

In economic as well as in ecological perspective, the resource consumption of products has to be planned to be more sustainable. Therefore products have to be designed to be resource and energy efficient along the total life cycle. To achieve this aim, it is possible to influence the energy and resource consumption in one or more product life cycle phases. The change of one product life cycle phase might also effect the energy and resource consumption in another phase in a positive or in a negative way. For this reason it is essential to evaluate all changes across the whole life cycle, to guarantee an overall reduction in energy and resource consumption [3]. The necessity for this can be shown by the following example: The manufacturing industry will primarily focus on the resource efficiency during the manufacturing process. The customers of energy or material consuming goods, like a machine tool on the other hand, intend to have low resource consumption during the use stage. The analyse of the whole life cycle including pre-products production, manufacturing itself as well as scenarios for use stage and end-of-life is therefore essential for the manufacturers of these goods [4]. With the increasing impact of material and energy costs in the use stage of a machine tool even in high wage countries, it is important to identify and optimise the energy and material demand. Former studies identified that manufacturing processes can be influenced most, if the processes with the highest average power consumption are optimised. Therefore heat treatments are generally considered with a high optimisation potential.

Within this paper further investigations of the project BEAT ("Bewertung der Energieeffizienz alternativer Prozesse und Technologieketten", engl.: Assessment of the energy efficiency of alternative processes and process chains), which is kindly supported by the Federal Ministry of Education and Research (BMBF) in Germany, are presented and it will be shown that this assumption is not sufficient for machining operations in the automotive sector.

2 A LIFE CYCLE ASSESSMENT APPROACH FOR THE EVALUATION OF THE ENERGY AND RESOURCE CONSUMPTION OF PROCESS CHAINS

Throughout recent years, the objective of manufacturing processes was to reduce the manufacturing costs. Due to a lack of data it was assumed that the major cost drivers are staff and machine costs. The detailed analysis of energy and material was not in the focus of optimisation potential. This can be proven best on the basis of the available inventory data in Life Cycle Assessment. Until today the data on machining of metal parts is poor.

A model for the prediction of the material and energy consumption with reasonable preciseness during a typical machining process like milling or turning is not yet available [5]. It is common practise within companies that costs for energy are assigned towards the machine tools rather by the amount of square meters used by the machine tool than by the real usage data.

It is generally known that the best procedure to compare different production processes with respect to their energy and material consumption and the associated environmental impacts is done by a Life Cycle Assessment according to DIN EN ISO 14040/14044. Within the Life Cycle Assessment material and energy flows of all life cycle phases are determined (compare Figure 2) and the environmental impacts are calculated by means of using scientifically based characterisation factors. Only the relative comparison of the results for the different impact categories enables the evaluation of the values [6][7].

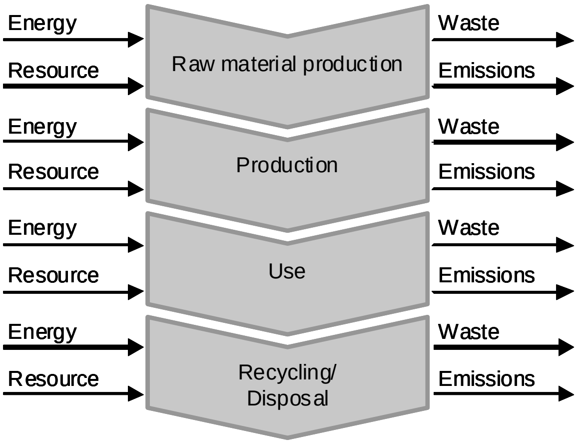

Figure 2: Balance shell for Life Cycle Assessment with in- and outgoing energy and resource flows.

As stated above, even from the cost perspective machining operations have not been in focus of the Life Cycle Assessment studies so far. Assumptions and estimations have to be used due to missing data for these processes.

Recent studies have shown, that the costs of energy used in machining operations are as high as the costs for tools [8]. For this reason it is absolutely crucial to further analyse and measure the energy and material consumption of typical machining processes. Alternative processing routes may become interesting on a cost perspective as well as for ecological reasons.

So far optimisations of technologies and process chains have been driven by the lowest production costs as a sum of machine costs and staff costs. This may change in future due to rising costs for material and energy.

A detailed data collection for process chains with reference to the considered products is necessary. This allows the extension for comparisons to alternative process routes and for a “technical” cost calculation. While the work load for such an inventory analysis may seem to be very high, its effect may be even bigger.

This approach will help the companies to reduce the consumption in two ways.

- Detailed measurements on the machines will identify “hot spots” within the processes and help to develop options for savings even in today’s state of the art processes.
- Better understanding on the material and energy consumption of different machining processes, which means the development of ecodesigns for whole process chains.

An additional benefit is a better understanding of hidden costs, in most cases declared as overhead, which also contain energy and auxiliary material (range from 5% to 50%).

3 INDUSTRIAL CASE STUDIES IN THE AUTOMOTIVE SECTOR

Within the BEAT Project the following two industrial case studies of the partners Bosch and Daimler were investigated. The case studies were chosen due to their high volume relevance of the parts.

3.1 Gear manufacturing

The research object of the Daimler AG is a production line for the manufacturing of the 4th gear wheel (idler gear) of the front-shift transmission (type FSG) in the Rastatt (Germany) plant. The FSG is the manual transmission of the A and B class, with an annual production volume of 100,000 units. The used process chain is displayed in Figure 3. The basic structure of the process chain is soft machining of the forged part and hardening followed by hard finishing processes, such as hole and gear grinding. Within the project the process chain from turning to gear grinding is captured and evaluated as this part of the process chain is done within the Rastatt production plant.

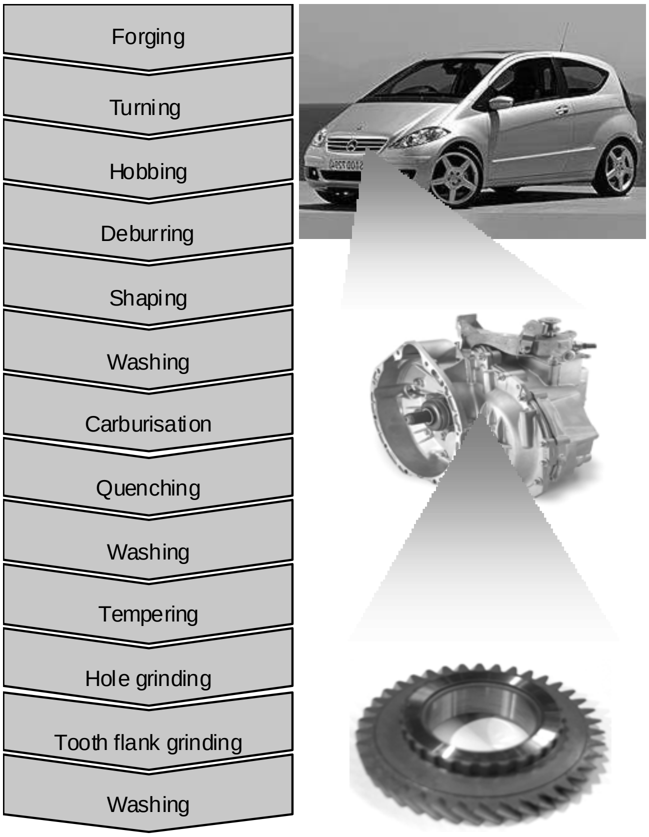

Figure 3: Case study gear manufacturing with its process chain.

3.2 Valve injector manufacturing

The research object of the Robert Bosch GmbH is a production line for the manufacturing of the valve injector of a magnetic common rail injector in the Bamberg (Germany) plant. Common rail systems are produced since 1997 and the total volume is clear about 50 million systems so far. The applied process chain is displayed in Figure 4. The basic structure of the process chain is soft machining of bar material and hardening followed by hard finishing processes.

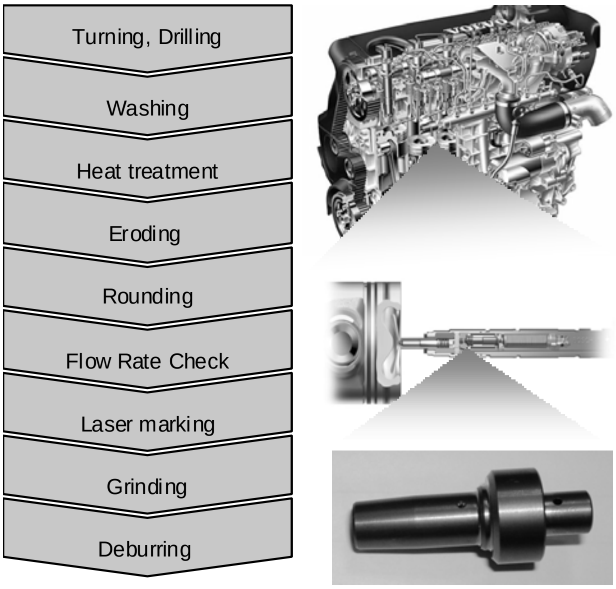

Figure 4: Case study valve injector manufacturing with its process chain.

4 ENERGY AND RESOURCE CONSUMPTION ALONG THE PROCESS CHAIN

For the evaluation of the process chain it was essential to define the balance shell first. It is not useful to respect only the energy and resources which are needed for the process itself, as the enabling energy and resources for a machine tool cannot be neglected for the process.

Within the BEAT project, the machine tools were chosen as the relevant balance shell for the evaluation. Besides it has been decided, that the first level of central systems (directly connected to the machine tool) is also measured and converted on the single machine tools by the consumption of functional units of each machine tool. Nevertheless it is not practical to measure even more layers of central systems as the influence and therefore the relevance of these systems is very small in comparison to the direct energy and resource flows.

As in most manufacturing plants the real energy and resource flows in the machine tool are not known, a first step within the BEAT project was the qualitative detection of all flows in and out of each machine tool and central unit. An extract of the example of the gear manufacturing can be seen in Figure 5.

Electrical energy is a major flow as it is required almost everywhere. Therefore its correct data acquisition is important and will be further investigated in the next chapter.

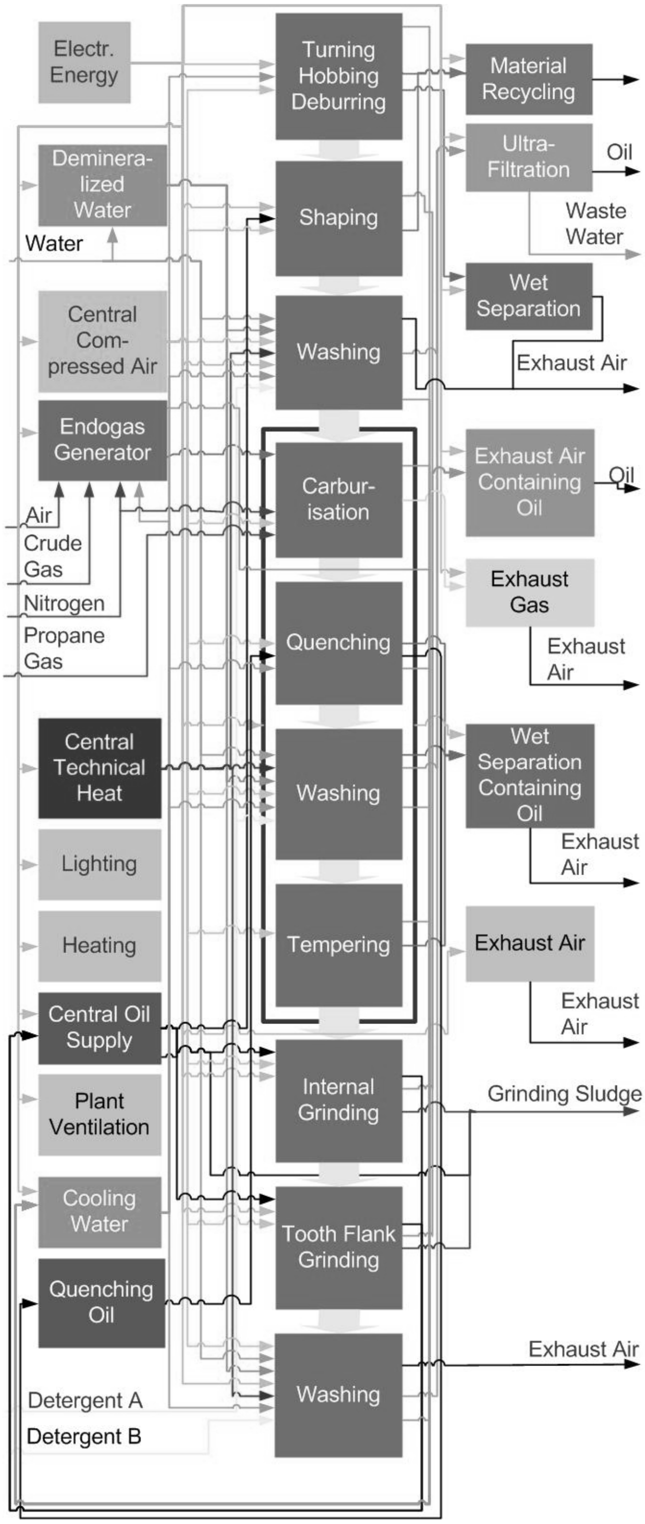

Figure 5: Energy and resource flows within gear manufacturing.

5 TECHNOLOGY REQUIREMENTS FOR DATA AQUISITION OF ELECTRICAL ENERGY

In general converter-fed motors are applied to modern machine tools to allow the required dynamic operation. From the electrical point of view a machine tool can be simplified as done in Figure 6, including the converter and one electrical machine, e.g. a speed variable main spindle.

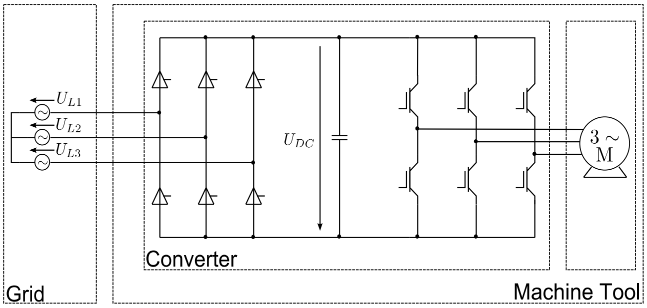

Figure 6: Simplified electrical representation of a machine tool.

For a significant data acquisition of the electrical energy flow, the voltage and current shapes have to be considered. The nearly sinusoidal input voltage of the converter is rectified in the first module. The converter feeds the connected motor with voltage pulses of a switching frequency of 2-16 kHz. These voltage pulses lead to a current flow which can be controlled in magnitude and frequency as it is required by the process. Due to the switched voltage the current has a high fraction of higher harmonics beside the fundamental wave. For a reliable data acquisition the sample frequency of the measuring instrument has to be adapted to this higher harmonics.

Electrical power measurement devices can be differentiated into power analysers and power quality analysers. A major difference is the sample frequency. Modern power analysers have sample rates up to 3 MS, resulting in a sample frequency of 500 kHz per channel for a 3-phase power measurement. This sample frequency allows a power measurement at the input and at the output of the converter. Power quality analysers, which have an extensive advantage in price compared to power analysers up to a factor of 5-10, are generally used for long term power quality measurements of power grids. They have sample rates of 128 - 512 samples per cycle, resulting in a sample frequency of 6.4 kHz - 25.6 kHz for 50Hz grids [9].

To understand the impact of the sample frequency on the measurement accuracy some basic principles of electrical power measurement have to be considered. The instantaneous input power of an electrical load is given by:

$$p_n(t) = u_n(t)\cdot i_n(t). \tag{1}$$

The phase voltage $u_n(t)$ and the phase current $i_n(t)$ are sampled with the sample frequency of the measurement instrument. It has to be considered that the error of the measurement will increase for a decreasing sampling frequency. The instantaneous power can be separated into active and reactive power. The active power less the internal losses of the electrical drive, e.g. friction, switching and ohmic losses, is dissipated into motion. The active power for each phase n is defined as

$$P_n = \frac{1}{T}\cdot\int_T u_n(t)\cdot i_n(t)dt. \tag{2}$$

For a holistic energy analysis the reactive power has to be regarded as well. The inductive behaviour of electrical machines causes a reactive current flow leading to additional ohmic losses onto the supply conductors. Reactive power oscillates between the grid and the load (machine tool) and is not converted into mechanical power. The reactive power is defined as

$$Q_n = \sqrt{S_n^2 - P_n^2}, \tag{3}$$

with the apparent power:

$$S_n = U_{rms,n}\cdot I_{rms,n}, \tag{4}$$

and the root-mean-squared values:

$$X_{rms} = \sqrt{\frac{1}{T}\int_T x(t)^2\,dt}, \quad x\in[u,i]. \tag{5}$$

The calculation of the root-mean-squared values has to be synchronised by the zero crossing of the voltage or the current. This synchronisation fails if the sample frequency of the measurement instrument is too small. By this reason it is not possible to use power quality analysers for power measurements at pulsed voltages behind the converter.

Beside the sampling frequency, the method of the current measurement has an arbitrative influence on the quality of the measured data. The use of serial connected high-precision shunt resistances necessitates an unacceptable disconnection of the machine tool from the grid. This interruption of the machining process can be avoided by using current probes. Current probes are often based on the principle of a transformer. Their accuracy is lower compared to shunt resistances due to stray fluxes and external influences. Compared to power analysers, which use generally shunt resistances, power quality analysers are equipped with current probes. To quantify the ability of power quality analysers to acquire the energy consumption of machine tools, a comparative measurement is performed. Using a simple configuration as depicted in Figure 6, the energy consumption is measured at the terminals of the converter. The process of a machine tool is simulated using a controlled asynchronous machine as a main spindle connected back to back to a controlled permanent magnet synchronous machine. The power analyser measures the current with Hall Effect current sensors with an accuracy of 0.3 %. The sample rate is adjusted to 500 kHz per channel. The power quality analyser works at sample frequency of 6.4 kHz per channel and uses current probes with an accuracy of ±0.7 % ± 2 mA and a phase angle error of ± 1.5º. The rms-values are averaged over a period of 1s. Figure 7 and Figure 8 depict the measured active and reactive input power at the converter terminals for different applied loads of the asynchronous machine.

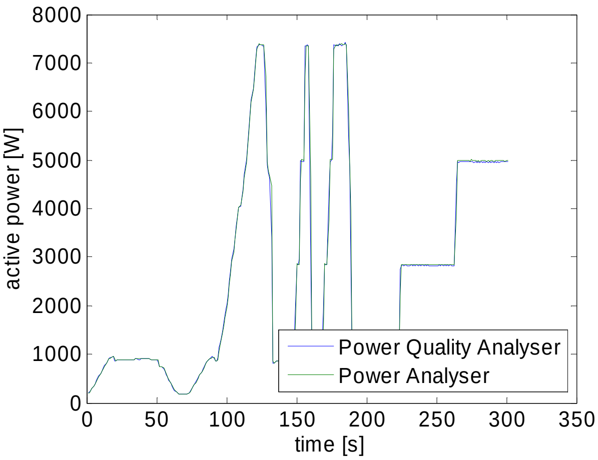

Figure 7: Energy measurement of the active power by a power analyser compared to a power quality analyser.

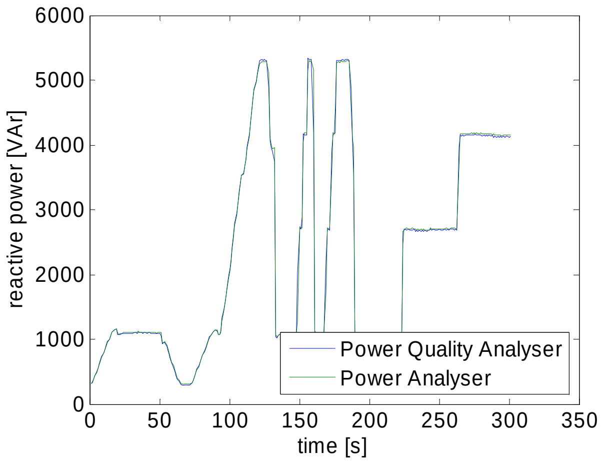

Figure 8: Energy measurement of the reactive power by a power analyser compared to a power quality analyser.

The relative deviation between the measured active energy is 0.14 %. The reactive energy has a relative deviation of 0.16 %. These matching results of the comparative measurement demonstrate the usability of power quality analysers at the terminals of machine tools within the project despite the lower sample frequency and the less accurate current measurement.

5.1 Power demand and energy consumption in a turning process

Figure 9 displays the composition of power demands, forming the overall process energy depending on the process times. During one cycle several different power demands can be distinguished. The electrical energy can be divided in energy which flows directly into the balance shell, in other words in the machine tool, and in indirect energy from the periphery (central unit systems) which is necessary to enable the manufacturing process.

On the one hand there is a constant portion containing periphery (illumination, air conditioning ...) and machine aggregates (basic demand = standby demand). On the other hand the variable portion depends largely on the actual process as well as on auxiliary and feed movements [10].

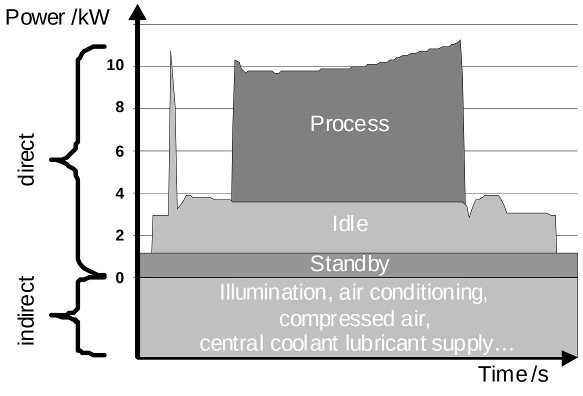

Figure 9: Power consumption in cutting processes.

The energy consumption per part in manufacturing can be calculated as the sum of the direct and indirect energy per part.

$$E_{part} = E_{part,direct} + E_{part,indirect} \tag{6}$$

E_{part}: energy consumption per part

$E_{part,\,direct}$: direct energy consumption per part

$E_{part,\,indirect}$: indirect energy consumption per part

The direct manufacturing energy per part is the sum of the energies of the single manufacturing processes

$$E_{part,\,direct} = \sum_{j=1}^{m} E_{part,man_j} \tag{7}$$

$E_{part,manu\_j}$: direct energy consumption per part in manufacturing process j

The energy of a single manufacturing process consists of the real process energy, the energy consumed in the idling mode and a proportional part of the energy consumed in standby mode and while the machine tool is switched off.

$$E_{part,man_j} = E_{process,j} + E_{sb,j} + E_{idle,j} + E_{off,j} \tag{8}$$

$E_{process,j}$ process energy consumption

$E_{idle,j}$ energy consumption during idling

$E_{sb,j}$: energy consumption in standby mode

$E_{off,j}$: energy consumption while machine tool is switched off

If the idling and process mode cannot be separated, both energy consumptions can be calculated by the mean process and idling power multiplied with the time per unit. The energy consumption of the other machine tool state can be proportionally added.

$$E_{part,\,man_j} = P_{process,\,mean} \cdot t_{process} + \frac{p_{sb}}{p_{process}} \cdot t_{process} \cdot P_{sb,\,mean} + \frac{p_{off}}{p_{process}} \cdot t_{process} \cdot P_{off,\,mean}. \tag{9}$$

$P_{process,\,mean}$: mean process power

$P_{sb,\,mean}$: mean standby power

$P_{off,\,mean}$: power consumption while the machine tool is switched off

$t_{process}$: process time

p_{sb}: proportion of standby

p_{off}: proportion of the machine tool is switched off

$p_{process}$: proportion of the productive time

The indirect energy from the periphery has to be estimated by defining a functional unit (FU) of each auxiliary energy and resource flow. A functional unit for compressed air is for example Nm³.

$$E_{part,indirect} = \sum_{i=1}^{n}\sum_{j=1}^{m} \frac{E_{aux,i}}{FU_{total,i}} \cdot FU_{machine\,tool_j,\,part} \tag{10}$$

$E_{aux,j}$: energy consumption of auxiliary device j

FU_{total}: total amount of functional units

$FU_{machinetool,\,part}$: amount of functional units used on a machine tool for a product

The following chapter will show the results of measurements of the direct energy for the valve injection process chain, which were generated up to now. Further research work is outstanding.

5.2 Energy consumption within valve injector manufacturing

Corresponding to the described proceeding above, every process was measured and calculated within both case studies. In the following Figure 10 and Figure 11 the results are shown for the valve injector process chain. The results are especially interesting if the average power consumption of the single processes is compared with the influence on the energy per part.

As it can be seen, the extensively used assumption, that the optimisation of the highest power consumers would bring the best benefit, does not really make sense, if the energy per unit is taken into account.

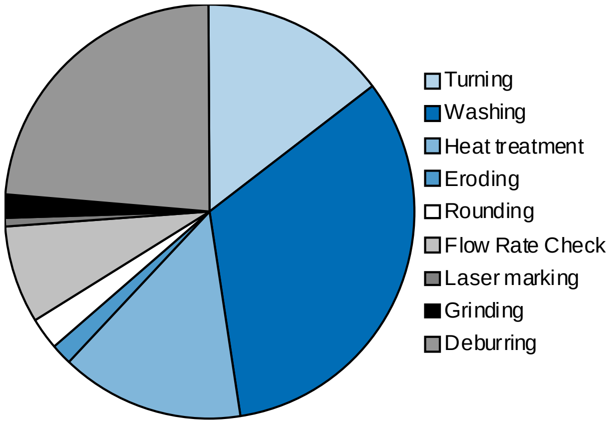

Figure 10: Distribution of power consumption along the process chain.

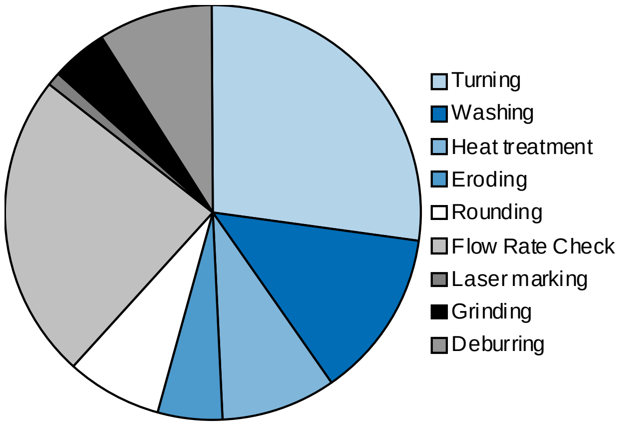

Figure 11: Distribution of influence of the processes on the required energy per part.

The reason why high energetic processes, as heat treatment, in the shown case studies didn't have such a big influence on the direct electrical energy per part is that in the heat treatment and washing process much more parts are treated at the same time than on a machine tool.

6 SUMMARY AND OUTLOOK

This paper presented and discussed research work within the framework of the BMBF supported project BEAT. It was possible to show a suitable proceeding for the assessment of energy demands of manufacturing processes with the focus on the energy per unit.

The case studies showed that the energy per unit is quite different from the average power consumption of a process, as the units in a process might have an even bigger impact on the energy per unit as the amount of power consumption.

Nevertheless, for a comprehensive balance of manufacturing processes further information are still missing and have to be generated in the future.

7 ACKNOWLEDGMENTS

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8 REFERENCES

[1] Herring, H., (2000) Is Energy Efficiency Environmentally Friendly? Energy & Environment 11, No. 3, pp. 313 - 325

[2] Herrmann, H., Zein, A., Thiede, S., Bergmann, L. Bock, R., (2008) Bringing sustainable manufacturing into practice – the machine tool case, in: Sustainable Manufacturing VI, Global Conference on Sustainable Product Development and Life Cycle Engineering, Pusan, Korea, pp. 272 - 277

[3] Graedel, T., (1996) Industrial Ecology: Defnition and Implementation, in: Socolow, R. et al.: Industrial ecology and global change, Cambridge University Press, pp. 23 - 42

[4] Gerschwiler, K., Jahns, P., Klocke, F., Lingg, G., Lung, D., Schlosser, R., Werner, A. R., Zeller, R., (2008) Ressourcenschonende Produktion, in: AWK 2008 – Wettbewerbsfaktor Produktionstechnik, pp. 81 - 124

[5] Büdicker K., (2003) Reduktion und Verwertung von Abfällen anhand ausgeführter Beispiele der Wälzlagerherstellung, VDI Berichte Nr. 1779

[6] N.N., (2009) Environmental management – Life cycle assessment – Principles and framework, DIN ISO EN 14040

[7] N.N., (2006) Environmental management – Life cycle assessment – Requirements and guidelines, DIN ISO EN 14044

[8] Bode, H.-O., (2007) "Einfluss einer energieeffizienten Produktion auf Planungs- und Produktprämissen am Beispiel der Motorenfertigung"; in XII. Internationales Produktions-technisches Kolloquium, Berlin, pp. 299-305

[9] N.N, (2009) IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std 1159-2009

[10] Bhattacharya, A., Das, S., Majumder, P., Batish, A., (2009) Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA, In: Production Engineering, Vol. 3, No. 1, pp. 31 - 40