Case study based comparison of life cycle analyses within metal manufacturing in the automotive industry

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Abstract
In a world with increasing importance of global competitiveness due to saturated as well as emerging markets, especially the orientation towards energy and resource efficiency is a key driver for future competitive advantages. By reason of rising energy and material prices, state-of-the-art manufacturing processes have to be improved regarding efficiency in order to remain profitable. Therefore actual consumptions have to be transparent for the deduction of saving potentials. This paper presents a clear methodology to evaluate the ecological impacts of process chains in manufacturing caused by energy and material consumptions. Due to the complexity of these consumptions throughout the life cycle of products it is necessary to assess the ecological impacts from a life cycle perspective. Therefore the procedure is aligned to the methodology of a life cycle assessment. Additionally the evaluation of the ecological outcome has to be adapted to the industrial environment. Not all the impact categories of life cycle assessments are suitable for the direct evaluation of manufacturing processes and chains. Companies need a detailed overview about the actual energy and material flows and their origins within manufacturing which is not yet available. With this knowledge main consumers can be identified and specific strategies for the reduction of resource consumption can be derived. Moreover, the paper presents industrial case studies which demonstrate the explained methodology and its benefit

Keywords
Manufacturing, Life Cycle Analysis, Automotive Industry

1 INTRODUCTION

Public discussions about ecological performance of products as well as rising prices for materials and energy urge companies towards higher awareness of their ecological impact and efficiency. The automotive industry takes up an important role in this development and adapts manifold measures to reduce the ecological impacts on the environment of their products in both the manufacturing and the use phase.

Whereas the fuel consumption and the connected carbon dioxide emissions are established as decisive selling argument, the activities aiming to reduce the ecological impact of the manufacturing phase are not as visible but equally important in reducing the overall impact along the entire life cycle of a product. However, the environmental performance of products having a high impact during the use phase is significantly influenced by the manufacturing. Hence, manufacturing technologies are a suitable lever for the overall reduction of ecological impact. [1]

For the suitable assessment of a given product, the entire life cycle needs to be considered. Either a holistic life cycle assessment needs to be carried out or the results of the assessment of the phases production, use and recycling/disposal need to be aggregated. It might be worthwhile, for example, to add another manufacturing step to the technology chain of a product, worsening the impact in the production phase, but improving the impact in the use phase. The surface treatment of the cranked shaft of an automobile, which requires additional effort in manufacturing, may lead to a reduction of fuel consumption during use phase overcompensating the negative effect of the extra treatment. [2] Therefore conclusions must not be drawn unless the entire life cycle is accounted for. [3, 4]

The extensive procedure of the life cycle assessment according to the ISO 14040 standard prevents companies from assessing their products. Especially the time consuming data acquisition and little knowledge about the appropriate scope of the study is a barrier for companies. Within this paper three case studies of the automotive sector are presented and compared. As part of public funded projects, the three products have been investigated with a high level of detail in order to derive which data is highly relevant or negligible for the outcome of the study. The case studies offer a good opportunity to conduct this analysis because although all of them are located in the automotive industry, the investigated products differ significantly in terms of annual production volume, material and size.

2 TECHNOLOGY CHAINS OF THE CASE STUDIES

In this paper, three case studies conducted within the automotive industry are presented. In the project BEAT, funded by the Federal Ministry of Education and Research (BMBF), the technology chains of the 4th gear wheel (idler gear) of the front shift transmission of Daimler AG's A and B class as well as an injection nozzle for a magnetic common rail injector produced by Robert Bosch GmbH were investigated. Furthermore the entire life cycle of a forming tool for car body parts was studied with kind support of Volkswagen AG, Audi AG and Römheld & Moelle GmbH in the project InnoCaT supported by the BMBF likewise. The technology chains of the three products balances are displayed in Figure 1.

Figure 1: The technology chains of the three case studies

The manufacturing technologies used in the three technology chains cover forming, metal cutting, grinding, heat treatment, EDM, laser treatment, washing processes as well as casting and thus a representative mix of manufacturing technologies.

The three products vary extensively in terms of weight and annual production volume, and therefore give a good opportunity to conduct a reference analysis with the results of the life cycle assessment. The focus of the study BEAT was laid on the production phase, the use phase was not considered. However, the results of the production phases can be linked to those of the usage phase for a holistic life cycle assessment. Within the project InnoCaT, a life cycle assessment in the narrower sense was conducted, covering the phases production, usage and recycling/disposal. Constituting facts about the three products are listed in Table 1.

Table 1: Facts about the three case studies

	Gear Wheel	Injection Nozzle	Forming Tool
Production site	Rastatt, Germany	Bamberg, Germany	Mainz, Ingolstadt, Germany
Annual volume	ca. 100,000	ca. 5,000,000	< 10
Weight	ca. 600 g	ca. 50 g	> 20 t
Material	20MoCr4	100Cr6	Gray cast iron

Whereas the products gear wheel and injection nozzle are manufactured in industrial mass production, the forming tool is produced in low quantities and used in mass production during its use phase.

In contrast, the weight of the forming tool is much higher than the weight of the gear wheel and the injection nozzle. The materials cover case-hardened steel (20MoCr4), bearing steel (100Cr6) and gray cast iron. All the three products have in common, that the elementary outer shape is formed by machining processes which account for a significant share of the environmental impact along the manufacturing chain of the products. [5, 6]

3 DATA ACQUISITION AND EVALUATION METHODOLOGY

A typical and standardized approach for the analysis throughout the life cycle of products is specified by DIN ISO 14040/44. [7, 8] This standard provides a methodology for a life cycle assessment which has been applied to the three products and their technology chains. Since this publication focusses on specific results of the research, more detailed information about the conducted procedure can be found in previous works.[5], [6] In the cases of the injection nozzle and gear wheel a cradle-to-gate perspective from material creation and processing over the process steps at the respective companies up to the final product has been used. The usage phase has not been assessed, because the final influence on a whole car could not be measured. In contrast, the forming tool life cycle could be considered from cradle-to-grave and therefore includes the usage phase as well as the recycling. For the recycling phase however, only assumptions have been made, since the exact recycling and disposal procedure is handled differently for every forming tool. Also the time of usage for the post-serial production could not be assessed in detail, because it is not performed at the considered companies.

Regarding the data acquisition all three case studies essentially provided the same level of detail. All necessary and measureable energy and material flows have been acquired, assessed and were linked to the production of one final piece. Electrical energy, pressurized air, heating energy, cooling, detergents and lubricoolants are only a few of the measured flows. For the injection nozzle and the gear wheel also the central supply units such as pressurized air, technical heat and ventilation were assessed separately in order to provide specific data. This data basically links the consumptions of central units to the supplied media and subsequently allows to assign these consumptions to the production process. For the forming tool the central units have also been considered by using already available data for the supplied media.

Another important step in a life cycle assessment is the determination of the evaluation methodology to be used. Regarding the actual industrial practice, a whole life cycle assessment may demand too much specific knowledge of the final user in order to interpret the results properly. Simple and representative figures are needed in order to provide easy-to-understand and viable key indicators which can be used for initial assessments as well as the trace over longer periods of time. Therefore, in this paper not the total life cycle assessment is used for the interpretation of the results. Only the global warming potential (GWP, kg CO_2-equivalent) and the primary energy depletion (PED, MJ) are provided. These values have been created by using the life cycle software Gabi 5 by PE International AG. [9] Both of these impact categories are common and can be used to unify all energy and material consumptions of the technology chains. Due to the diversity of the consumed media this unification is one of the essential steps of industrial application. Although the other ecological impact categories available from the LCA will not be used, the representativeness of the global warming potential and primary energy depletion has been confirmed by analyzing the whole life cycle assessment. The GWP and PED have consequently been linked to one piece during the analyses in order to provide summarizing data for the product.

4 RESULTS

Within this section of this paper, the results of the three technology chains will be presented. Based on the findings a comparison between the studies will be conducted in order to draw conclusions which can be adapted to further technology chains in the industrial manufacturing of metal parts. The presentation will take place in three steps. Firstly the distribution of the consumptions caused by workpiece material and the processes will be elaborated in the manufacturing phase, secondly the main consumers within the processes of manufacturing will be highlighted and discussed, thirdly the process steps within manufacturing will be presented regarding their primary energy consumptions.

First results of the three manufacturing case studies are presented in Figure 2. For each case the global warming potential as well as the primary energy depletion are shown divided into processes and material per product. For the forming tool manufacturing also auxiliary material has been included. This material originates from the tryout-parts which have to be consumed to take the forming tool into operation. Since this material can neither be assigned to material nor the processes and also the tryout-material is more valuable than the forming tool material itself, the authors decided to implement a single category in this case to assure comparability.

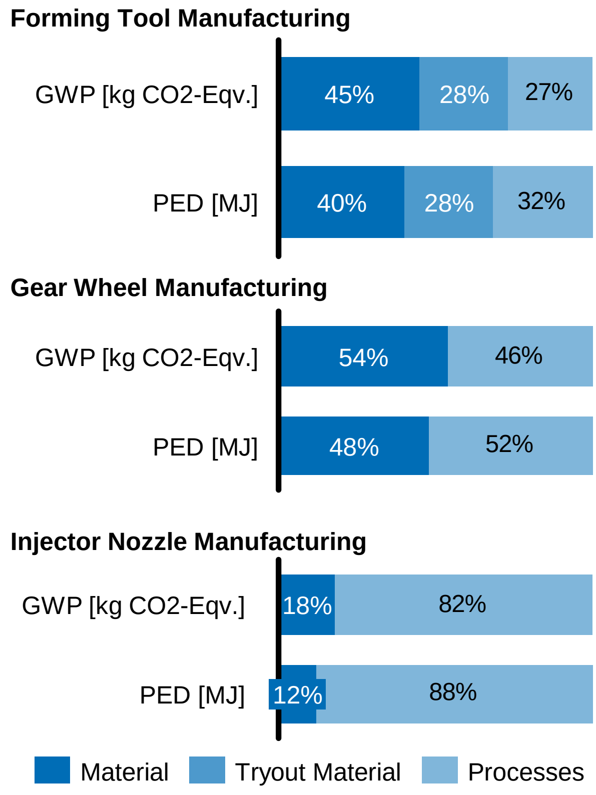

Figure 2: Manufacturing phase PED and GWP distribution of the three case studies

It can be observed that the share of the material is decreasing with lower part size and weight. This finding can be lead back to the material itself, but also to long machining times performed on machine tools. Therefore the smaller the parts are, the bigger the influence of idle time power consumptions are. This direct connection consequently is obvious in the whole analysis. It is inappropriate to transfer this finding into different branches other than metal manufacturing, but for the manufacturing of metal parts in respect to machining, heat treatment and washing processes the trend seems to be legit.

In addition to the previous illustration, in Figure 3 the contribution of the main consumers to the primary energy depletion of the manufacturing phase per part is presented. The workpiece material itself is not included into the consideration for the purpose of determining the main consumers. For every assessed technology chain these consumers are compared. Regarding the findings of the figure, it is necessary to point out several special attributes in order to be able to compare the different outcomes accordingly. Within auxiliary materials several materials, such as water, natural gas or lubricoolants are included.

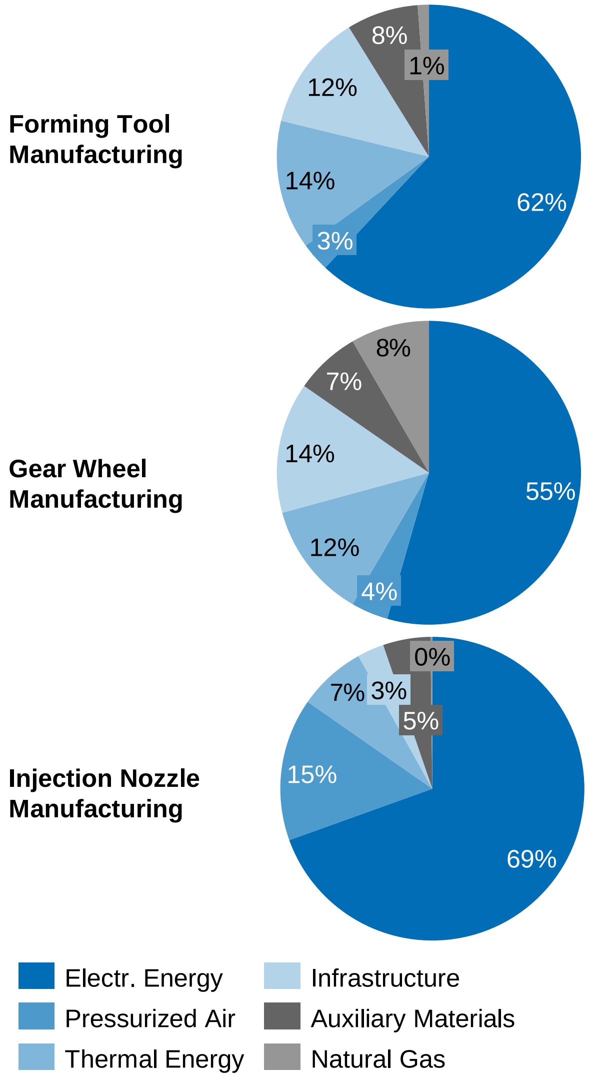

Figure 3: Shares of consumption types during manufacturing of the three case studies based on primary energy depletion (PED)

The first obvious result is that the electrical energy in all cases is the main contributor to the primary energy depletion. This fact can easily be underlined by regarding the technology chain and the used machines for manufacturing the products. Most of the used machines operate on electrical energy and only use other energies and materials for additional tasks, such as pressurized air for sealing, lubricoolants or thermal energy for heating and cooling purposes. Also in the metal manufacturing area, especially regarding machining, machine tools feature high idle power consumptions in comparison to the process itself and therefore are highly depending on the operating time.

Pressurized air accounts for only a small share of the total consumption profile of manufacturing the considered metal parts, except for the injector nozzle. In this specific case the pressurized air is used to transfer and clean the workpieces during the process, whereas in the other cases it is only used as additional medium for machine tools. Because of the small size of the injection nozzle this consumption can be observed in the given overview of the consumers.

Another specialty of the injection nozzle manufacturing is the significantly lower infrastructural consumption (lighting and heating) per part. This can be explained by shorter cycle times and therefore the smaller share of the plant lighting and heating which is assigned to a single piece.

The thermal energy covers direct heating energy as well as cooling energy. In these cases only the additional centrally supplied thermal energy which is not produced directly at the machines is considered. It can be observed that the share of these thermal energies has an influence between 7 % and 14 % on the total primary energy consumption per part.

For the gear wheel the consumption of natural gas has been presented separately, because of a heat treatment process based on natural gas inside the technology chain. The contribution of this consumer is not significantly high, but still cannot be neglected. In the technology chain of the injection nozzle the heat treatment is performed with electrical energy by induction.

In Figure 4 the shares of primary energy consumption per part for every process step for all three case studies are illustrated. Focusing on the manufacturing processes, the material has not been included. Hence, the machining including grinding is one of the most consuming processes. Naturally in metal manufacturing, most processes in a technology chain include chip removal and therefore can be assigned to machining and grinding. But despite the number of machining and other processes, the influence of washing and heat treatment is not dominant.

Regarding the forming tool manufacturing, machining is responsible for almost half of the primary energy consumption. In this case the large workpiece surface and extensive machining times due to complex geometries lead to high consumptions of electrical energy. In this technology chain the specialty of including the iron melting in the foundry process offers a direct comparison. Not including the work piece raw material and tryout-parts, the single melting process is even outweighed by the mentioned machining expenses.

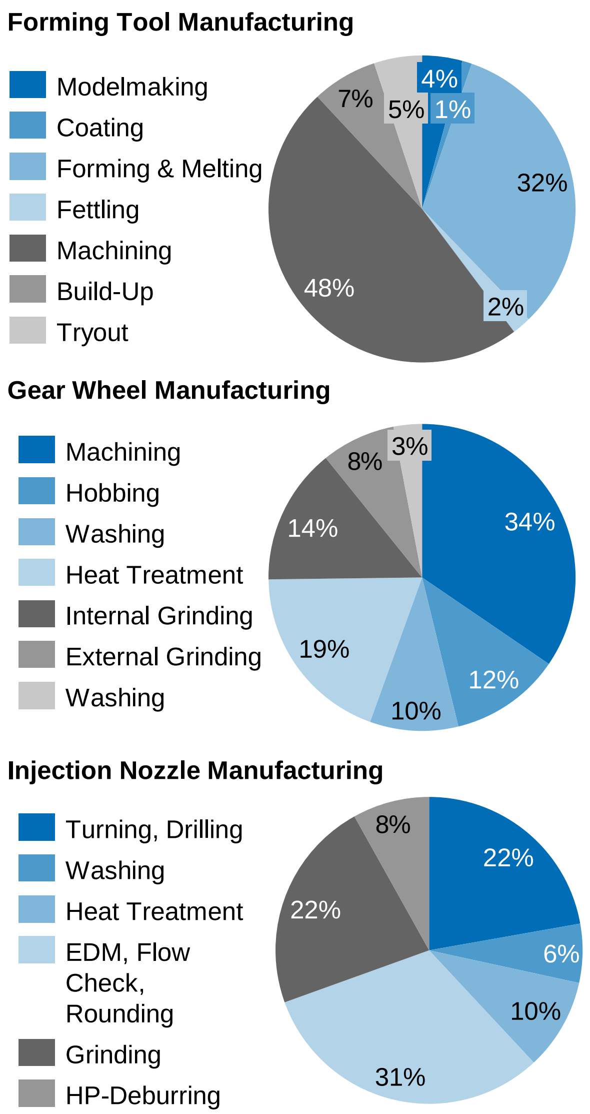

Figure 4: Shares of process consumptions during manufacturing based on primary energy depletion (PED)

5 CONCLUSION AND SUMMARY

Within this paper, beginning from the distribution of consumptions on the workpiece material and the processes in metal manufacturing, results based on three different case studies were presented. Especially when considering all assessed consumers as well as the process steps based on the global warming potential or primary energy depletion, the most contributing factors could be identified.

For finding improvement potentials in the industrial environment it is necessary to know which are the most consuming process steps and their corresponding energies and material expenses. With respect to the previously presented results, direct electrical energy is always one of the most significant contributors to primary energy consumption and emissions in metal manufacturing. In this field many approaches for simulation and estimation of consumptions, especially for machine tools have been developed.

The results show that not only electrical energy, but also pressurized air and thermal energy (cooling and heating) need to be considered within measurements and estimations.

Regarding the different process steps of the assessed technology chains, especially the machining still contributes significantly to the primary energy depletion in comparison to other processes. Therefore a holistic approach based on different levels of the processes is required. Both the process itself regarding process parameters, tooling strategies including the cutting material or the lubricoolant supply as well as the component level (reducing idle time power consumption, etc.) display potentials for future research and developments.

At this point the authors would like to emphasize that the presented findings should mainly be used for metal manufacturing technology chains. Especially chemical processes such as painting, coating and galvanization processes exhibit different consumption profiles and often directly emit gases and possible dangerous chemicals that underlie legislative regulations. In these cases more comprehensive procedures and extensive life cycle analyses are necessary. Finally, the transferability needs to be thoroughly verified for different technology chains.

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7 REFERENCES

[1] Herrmann; Thiede, S.; Luger, T.; Zein, A.; Stehr, J. (2009): Automotive Life Cycle Engineering. In: CIRP (Hrsg.): LCE 2009: 16th CIRP International Conference on Life Cycle Engineering. Life Cycle Engineering in the Sustainability Age. Kairo, 04.-06.05.2009, S. 157–164

[2] Wiedenhöfer T (2012) Funktionsorientierte Bauteilbewertung. Werkstattstechnik online 2012(1): 73–78

[3] Finnveden G, Hauschild MZ, Ekvall T et al. (2009) Recent developments in Life Cycle Assessment. Journal of Environmental Management 91(1): 1–21. doi: 10.1016/j.jenvman.2009.06.018

[4] Brecher C, Klocke F, Schuh G et al. (eds) (2011) Tagungsband Aachener Werkzeugmaschinenkolloquium 2011. Wettbewerbsfaktor Produktionstechnik Aachener Perspektiven. Shaker, aachen

[5] Klocke F, Schuh G, Döbbeler B et al. (2012) Simplified Life Cycle Analysis of a Forming Tool in the Automotive Industry. In: Dornfeld D, Linke BS (eds) Leveraging Technology for a Sustainable World. Proceedings of the 19th CIRP Conference on Life Cycle Engineering. Springer, pp 79–84

[6] Schlosser, R.; Klocke, F.; Döbbeler, B.; Riemer, B.; Hameyer, K.; Herold, T.; Zimmermann, W.; Nuding, O.; Schindler, A.; Niemczyk, M.; Schindler, B. A. (2011): Assessment of Energy and Resource Consumption of Processes and Process Chains within the Automotive Sector. In: Hesselbach, J.; Hermann, C. (Hrsg.): Glocalized Solutions for Sustainability in manufacturing. 18th CIRP. Berlin: Springer, S. 45–50

[7] Deutsches Institut für Normung (2009) Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen 13.020.10(14040)

[8] Deutsches Institut für Normung (2006) Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen 13.020.10(14044)

[9] GaBi 4 / GaBi 5: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP, Universität Stuttgart und PE International AG, Leinfelden-Echterdingen, 1999-2011. www.gabi-software.com.

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