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8.4 Sustainability of energy and material consumption within manufacturing processes

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Abstract
A model for the evaluation of machining processes with all direct in- and outgoing energy and material flows as well as the plant infrastructure installations is presented within this paper. The flows were captured, connected to functional units and evaluated in combination with a life cycle inventory data base regarding typical ecological indicators.
Former studies identified that the peripheries of manufacturing processes are responsible for the major part of the energy and resource consumption and that the process effectiveness is only dependent on the used machine tool and peripheral components. Within this paper it will be shown, that this assumption is not totally correct and that the generated efficiency values for the different processes are influenced in huge amount by process parameter variation.
Keywords:
Machining Processes, Sustainability, Life Cycle Assessment

1 INTRODUCTION

Since climate protection and reduction of carbon emissions have gained increasing significance in research, industry and legislation, it is not only important to reduce energy consumption and emissions of products during the use phase, but throughout the whole life cycle [1][2][3].

The Life Cycle Assessment (LCA) corresponding to DIN EN ISO 14040 and 14044 is a suitable method for the assessment of products [4][5]. So far the manufacturing phase of products is often neglected or only simplified respected within these LCA studies [6][7].

2 APPROACH

Besides the environmental also the social impact as well as the costs have to be respected to evaluate the sustainability of products or processes.

As changes for improvement of one product life cycle phase or production step might also effect the energy and resource consumption in another phase either positively or negatively it is essential to evaluate all changes done in one life cycle phase across the whole life cycle to guarantee an overall optimisation [8]. The most important life cycle phase during which product features still can be influenced is the manufacturing phase [9].

Due to both reasons above the evaluation of the sustainability of products is a very complex process which requires computational support. So far several software tools were developed to support LCAs (GaBi, Umberto, SimaPro etc.). These software tools use own or open source databases with life cycle inventory data of different material and energy flows. So far manufacturing processes are not available within these software tools or are aggregated together with the work piece material.

Therefore the aim of this paper is to setup a parameterised model of machining processes within the manufacturing

phase. The GaBi V5 Software of PE International is chosen for the implementation as this software tool is prepared for the evaluation of all three dimensions of sustainability by LCA, Life Cycle Costing (LCC) as well as a social Life Cycle Assessment (SLCA).

Although the possibility of a SLCA is prepared within the GaBi Software so far there is no common respected evaluation category for the social dimension existing. The common basis for the social evaluation is the fulfilment of basic needs corresponding to the SA 8000 norm. Therefore the SLCA is not further addressed within the paper [10].

3 PROCEEDING

For the further evalution the balance shell is used as drawn in Figure1. The raw material extraction is respected by the use of life cycle inventory data within the GaBi software. The main focus of the modelling is the production phase of a product. Within this phase machining operations were analysed to identify all direct material and energy in and outputs. The following possible direct inputs were identified and modelled with parameters:

- Workpiece material
- Electrical energy
- Lightning
- Compressed Air
- Air Conditioning
- Exhaustion
- Lubricoolant
- Technical Cooling
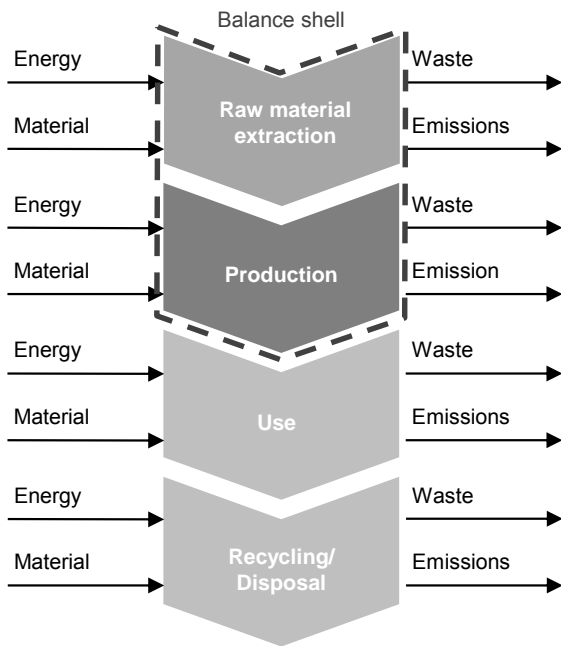- Technical Heating
- Heating
- Tools

Figure 1: Balance Shell in the product life Cycle corresponding to [11][12].

Direct outputs of the machining process are:

- Product
- Emissions
- Waste for thermal use
- Waste for recycling
- Waste for disposal

These in and outputs were analysed and connected by functional units with the machining process. Also indirect inputs as e.g. the electrical energy for the production of compressed air are respected. The consumption of the single material and energy flows S_k can then be calculated corresponding to equation (1).

$$S_k = \sum_{i=1}^{n} \int^{t_i} \dot{S}_{k,i}(t)dt \tag{1}$$

Within the single models parameters were used, which base on own measurements but should be adopted to the companies characteristics once. All material and energy flows were described with parametric models [13][14] and attributed to existing life cycle inventory data [12].

Only for the Wolfram Carbide (tools) and Krypton (Coating) no life cycle inventory data exist so far. Therefore approaches of Dahmus, Narita and Karpuschewski were taken for a assumption of the Primary Energy demand of the tool influence [15][16][17][18]. Therefore the category for the ecological evaluation is the Primary Energy, although the GaBi V5 Software allows much more categories. Intensive studies already demonstrated that the Primary Energy is a valid dimension for the overall ecological evaluation [19][20].

The use as well as the recycling and disposal phase are neglected within the evaluation, as the paper aims for the identification of the required material and energy for given tasks.

The cutting process is designed as a generic model which can be used for turning, milling, or drilling by using a switch.

Further on a few parameters (work piece geometry, material, used machine tool) have to be set to make a first assumption. Also detailed process parameters can be added to make a more valid calculation.

4 OPTIMISATION

For the energetic evaluation of cutting processes the specific cutting energy e_c is defined as the quotient of the cutting work W_e and material removal V_{cut}.[21][22][23][24].

$$e_c = \frac{W_e}{V_{cut}} \tag{2}$$

For the whole ecological evaluation the specific Primary Energy q_p is defined as the quotient of all Primary Energy demands $Q_{p,i}$ and the material removal m_{cut}.

$$q_p = \frac{\sum Q_{p,i}}{m_{cut}} \tag{3}$$

The Primary Energy can be plotted depending on the process parameters. Within Figure 2 the specific energy is shown over the feed and the depth of cut. The red square marks the possible variation of the insert and the red bubble the preferred cutting conditions. It can be seen that within the possible process parameters the specific energy varies by the factor 5 to 6. It can also be seen that the cross section of cut corresponds very well with the contour line of the specific energy. With higher feeds and a bigger depth of cut the specific energy is falling. So far the simplified Taylor Equation (4) is used for the description of the tool life [25]. Therefore an influence of the feed and the depth of cut is neglected.

$$T = C_v \cdot v_c^k \tag{4}$$

Spec. Primary Energy q_p / (MJ/kg)

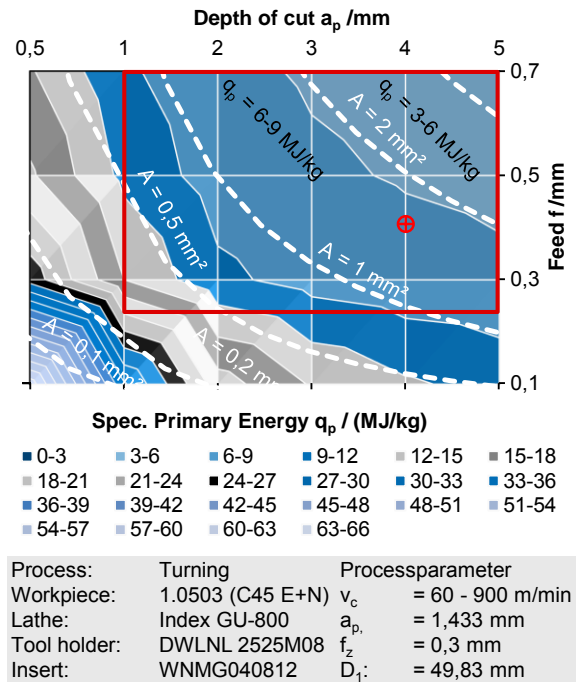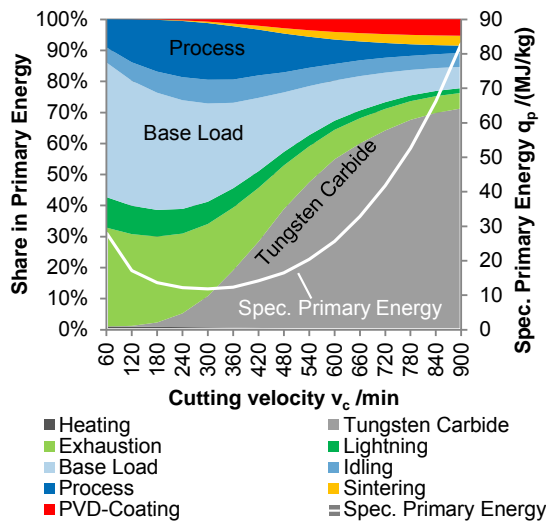| Process:	Turning	Processparameter
Workpiece:	1.0503 (C45 E+N)	v_c = 60 - 900 m/min
Lathe:	Index GU-800	a_p, = 1,433 mm
Tool holder:	DWLNL 2525M08	f_z = 0,3 mm
Insert:	WNMG040812	D_1: = 49,83 mm

Figure 2: Specific Primary Energy of the turning process dependent on feed and depth of cut [12].

In Figure 3 the Specific Primary Energy is plotted as a white line over the cutting velocity. In the background the composition of the Primary Energy demand is shown in the background. While the base load and exhaustion is responsible for the Primary Energy demand at low cutting speeds the Tungsten Carbide is the main driver for high cutting speeds. Although the process load is rising with higher process parameters the influence on the Specific Primary Energy is falling with high process parameters again.

Process:	Turning		Processparameter
Workpiece:	1.0503 (C45 E+N)	v_c	= 60 - 900 m/min
Lathe:	Index GU-800	$a_{p,}$	= 1,433 mm
Tool holder:	DWLNL 2525M08	f_z	= 0,3 mm
Insert:	WNMG040812	D_1:	= 49,83 mm

Figure 3: Specific Primary Energy of the turning process dependent on cutting velocity and origins [12].

Due to the different influencing factors on the Specific Primary Energy an local minimum can be identified by resolving equation (5).

$$0 = \frac{d \sum_{i=1}^{n} q_{p,i}(v_c)}{dv_c} \ and \ \frac{d^2 \sum_{i=1}^{n} q_{p,i}(v_c)}{dv_c{}^2} > 0 \qquad (5)$$

A sensitivity analyses showed that the complete model is able to reach good results in identifying the optimal process parameters together with the belonging Primary Energy consumption, even if the assumptions for Tungsten Carbide and Krypton contain big errors. Only for high cutting velocities which are not relevant from the technical point of view, high deviations between the simulations can be seen.

5 DISCUSSION OF THE RESULTS

The parametrical model proved that the common assumption, that all cutting processes have a constant ecological impact which is independent from process parameters is wrong.

The simulation was also able to show the different influence of machine tools on the ecological impact, even if the process parameters were kept constant. To decide which

machine tool should be used, also the costs have to be taken in account. A valid tool to compare different alternatives in these two dimensions is the LCC portfolio [26]. This allows comparing quantitative values in the dimensions Cost and Ecology. Nevertheless a common question is always rising. How can two different dimensions be compared and weighted? Or more practical: How much is one MJ Primary Energy worth in €?

Therefore a sustainability portfolio is proposed in the following. Basing on the LCC Portfolio the axis are scaled. Therefore a ratio was introduced. For this proposal it is assumed, that the minimum Primary Energy is required in the case, that a part or product can be used directly after the raw material extraction. This means the minimum required Primary Energy is in the material of the final product. The same assumption is taken for the dimension of the costs so that the best alternative can be chosen between different products or processes A, B, C ... , compare Figure 4.
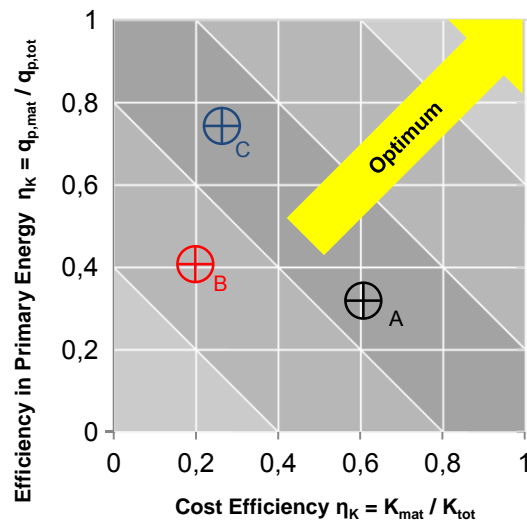

Figure 4: Specific Primary Energy of the turning process dependent on cutting velocity and origins [12].

6 SUMMARY

Within the paper an approach for the prediction of the sustainability of machining processes was shown. The results show in detail, that process parameters of cutting processes have an high influence on the Primary Energy Consumption and therefore also on their ecological impact. Detailed information on the modeling and results are recently published in [12].

Within the discussion of the results a further development of the LCC-Portfolio to a Sustainability Portfolio was presented which solves the problem of weighting two different dimensions.

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