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Critical comparison of methods to determine the energy input for discrete manufacturing processes

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ABSTRACT

High variation can be observed in energy requirement values reported for unit processes as applied in discrete manufacturing. Different methods for determining such values have been suggested, ranging from theoretic energy determination till statistically determined time averaged values based on experimental process measurements. In this paper the theoretic process energy method is compared to results as obtained from two methods suggested for systematic determination of Life Cycle Inventory (LCI) database entries for unit processes. Examples from different process categories are presented to illustrate the discrepancies observed between the approaches and to illustrate the error range linked to the method selection.

1. Introduction

Discrete part manufacturing processes consume a significant amount of energy and resources. From the industrial electricity consumption in Europe (EU-27) in 2008 it can be concluded that the metal processing industry is responsible for about 14.3% or 164 billion kWh [1]. Assuming a 3500 kWh electricity consumption per 4-member household each year, this equals to the electrical energy consumption of approximately 46.9 million households. At the same time, a trend can be observed towards more energy intensive processing techniques, so the energy consumption and related environmental impact of the manufacturing sector is in consequence growing steadily [2].

Nevertheless, a movement towards environmentally benign manufacturing can be observed nowadays [3]. Besides more stringent regulations (e.g. EU 20/20/20 target [4]) and incentives (e.g. ISO/CD 14955-1 standardization effort [5]), also competitive economic advantages (e.g. increasing energy and resource prices) as well as proactive green behaviour (e.g. corporate image) can be considered as important drivers in this context.

Environmental assessment of standalone unit manufacturing processes as well as full process chains still indicate significant improvement potential at machine tool architecture [6,7], process control [8,9] as well as production planning level [10,11], leading to more energy efficient manufacturing operations.

At all of these levels different methods for determining energy requirement values have been suggested, ranging from theoretic energy determination based on process physics [12] till statistically determined, time averaged values based on experimental measurements on machine tools running under industrial conditions [13]. In this paper, the theoretic required process energy, which can be seen as the optimal lower bound, is compared to results obtained from two methods suggested for systematic determination of LCI database entries for discrete unit manufacturing processes. While the first method, the so-called “Screening Approach”, relies on representative, publicly available data (e.g. machine tool data sheets, maintenance manuals and peer reviewed papers) and theoretic engineering calculations, the second one, the “In-Depth approach”, determines the process energy consumption based on detailed process time as well as power measurements. A detailed description of both approaches is provided by Kellens et al. [13]. Finally, where possible, the obtained energy consumption values are compared with the available data records of one of the most widely consulted LCI databases EcoInvent2.0 [14].

2. Process analysis

This section reports electrical energy requirements for six different manufacturing processes: Turning; Milling; Laser Cutting; Bending; Selective Laser Sintering (SLS) and Injection Moulding, using the different approaches described in Section 1. Detailed working principles and process descriptions can be found in [15]. The results of the analysis are presented in Table 1 as well as Fig. 1.

2.1. Turning and milling

Turning and milling are the most extensively applied material removal processes in manufacturing. The theoretical energy for subtractive processes is equal to the amount of work required to remove the material, which mainly contains the shear and friction energy [16]. The theoretical energy per removed material volume,

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Table 1
Specific electrical energy demands.

	Turning	Milling	Laser cutting	Bending	Injection moulding	SLS
Material	Carbon steel		Steel S235JR	Stainless Steel	PS	PA 12
Functional unit	kg of removed material			Bend of 1000 kN	kg of product material	
Case study specifications	Brinell hardness: 200 MRR: 230 cm^3/min (roughing) to 0.75 cm^3/min (finishing)		Sheet thickness: 1 mm Cutting length: 30 m	Sheet thickness: 6 mm Bend length: 1485 mm V-die: 48 mm Bend angle: 120° Bend time: 8 s No hold time	T_{melt}: 200 °C	Product weight: 3 kg
Theoretical approach	264 kJ	264 kJ	1330 kJ	14 kJ	302.8 kJ	396 kJ
Screening approach	0.48–47.71 MJ	0.62–74.75 MJ	85–180 MJ	57 kJ	NA	14.5 MJ
In-depth approach	0.44–30.25 MJ	0.47–39.84 MJ	74–157 MJ	56–217 kJ	0.72–3.39 MJ	52–238 MJ
EcoInvent2.0 [14]	CNC: 6.41 MJ Conventional: 1.22 MJ	1.71 MJ	93–145 MJ	NA	5.3 MJ	NA

e_{th} can be calculated as shown in Eq. (1) [16].

$$e_{th} = e_s + e_f = \tau\gamma + \left(\frac{F_c r}{bt}\right) \quad (1)$$

where e_s is the specific shear energy (J/cm^3) and e_f is the specific friction energy (J/cm^3); τ and γ are the shear strength (MPa) and shear strain; F_c is the cutting force component parallel to the tool face (N); r is the cutting ratio; b and t are the cut depth (mm) and feed (mm/rev), respectively. The shear energy during cutting accounts for 65–80% of the total specific energy [16]. Branham et al. [17] defined the shear energy as a function of the Brinell hardness (HB) of the material: e_S [kJ/cm^3] = (0.005–0.01) *HB*. For example, the theoretical specific energy for carbon steel with a Brinell hardness of 200 is 264 kJ/kg.

Kalla et al. [18,19] determined the electrical energy demand for turning and milling processes using the screening approach. Eq. (2) shows the formula to calculate the specific energy consumption e_{sc} which consists of three parts: the cutting energy, the idle energy (all systems active but no effective cutting and excluding the basic energy) and the basic energy (auxiliary systems running, no active positioning or cutting).

$$e_{sc} = e_p + \left(\frac{P_{idle}}{MRR}\right) + \left(\frac{P_{basic}}{MRR}\right)\left(1 + \frac{t_s}{t_m}\right) \quad (2)$$

where e_p is the specific cutting energy (J/mm^3); *MRR* is the material removal rate (mm^3/s); t_s and t_m are the standby and machining time; P_{idle} and P_{basic} are the average power consumption levels for idle and basic modes, respectively.

While, among others, Mativenga and Rajemi [20], and Kara and Li [21] performed in-depth process energy measurements on turning processes, the energy demand of milling processes is analysed by e.g. Mori et al. [8], Diaz et al. [9], Kara and Li [21], and Dahmus and Gutowski [22]. Taking into account the standby energy (up to 30% of the total production time is spent in standby mode [20]), the specific energy consumption, based on process measurements as applied during the in-depth approach, e_{in} can be derived using Eq. (3).

$$e_{in} = \left(\frac{P_m}{MRR}\right) + \left(\frac{P_s}{MRR}\right)\left(\frac{t_s}{t_m}\right) \quad (3)$$

where P_m and P_s are the total machine tool power (W) during machining and standby modes.

Table 1 as well as Fig. 1 present a quantitative analysis of the specific energy values for turning and milling processes using carbon steel. Different *MRR*, recommended by the tool supplier [23], ranging from 0.75 cm^3/min (finishing) to 230 cm^3/min (roughing) are applied for the screening as well as in-depth energy analysis.

While the EcoInvent 2.0 LCI database [14] contains an electrical energy consumption of 1.706 MJ/kg for average milling operations, the values for CNC and conventional turning are 6.408 and 1.217 MJ/kg, respectively.

2.2. Laser cutting

The case study for laser cutting is to perform a cutting process on a 1 mm thick steel sheet, with a cutting length of 30 m. The workpiece material is low carbon steel, S235JR.

By assuming there are no conduction losses and no material ablation, the theoretical specific energy of laser cutting is the combination of required energy to bring the kerf to its melting temperature and for the phase transition, as shown in Eq. (4) [24]:

$$e_{th} = m_{kerf} c_p (T_m - T_o) + m_{kerf} h_f \quad (4)$$

where for the corresponding workpiece, melting temperature T_m = 1808 K; ambient temperature T_o = 293 K; specific heat capacity c_p = 0.7 kJ/kg K; and the enthalpy of fusion, h_f = 270 kJ/kg. Based on these values, the specific theoretical energy e_{th} is 1330 kJ/kg.

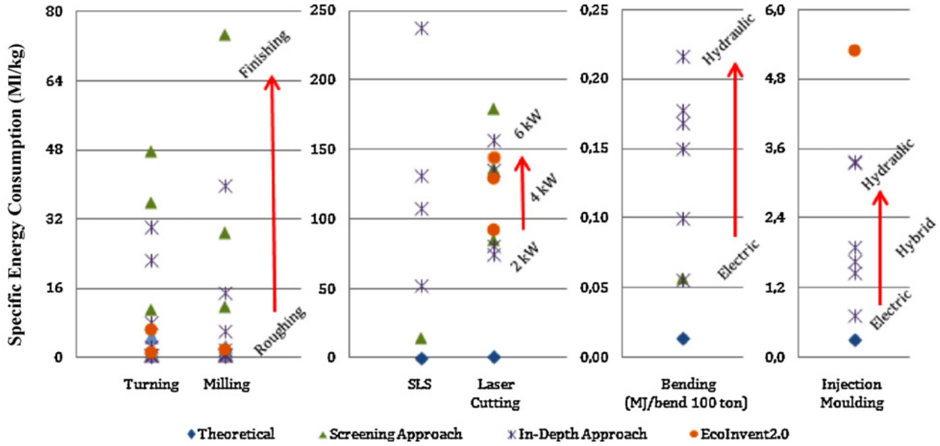

Fig. 1. Specific electrical energy consumption (MJ/kg) based on different approaches for a range of production processes.