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## DETERMINATION AND EVALUATION OF CO<sub>2</sub> AS A SUSTAINABLE PERFORMANCE MEASURE ON THE BASIS OF A TYPICAL LATHE

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**Abstract.** *This paper contributes to the assessment of possible sustainable performance measures from direct data acquisition at shop-floor level in order to enable the evaluation and further interpretation by the manufacturing management at plant level. Herewith, the possible performance measure related to the CO<sub>2</sub> equivalent and energy consumption is evaluated on the basis of the energy consumption of typical machining processes on a conventional lathe. Starting with the machine tool and its components as the lowest acquisition level, this paper proposes a possible conversion and interpretation of the gathered measurement data while simultaneously considering the regional differences in energy generation, which impacts on the CO<sub>2</sub> equivalent.*

*The evaluation of the sustainability related manufacturing performance is described exemplarily by calculating the CO<sub>2</sub> equivalent based on the energy consumption of a single manufacturing process. Relying on the assumption that it is possible and reasonable to calculate a CO<sub>2</sub> equivalent for every other manufacturing process analogously; an approach is*

*presented to connect the thereby gained CO<sub>2</sub> equivalents with every single produced product type.*

## 1 INTRODUCTION

As higher forces, speed, productivity, flexibility, reliability, and quality were the major sales pitches in market boom years, energy became an economic factor in market crises. The focus has changed again, just as in 1970, sustainable production and corresponding sustainable manufacturing systems are an emerging trend that becomes increasingly important in current industry practice. Sustainability is therefore not new and it is commonly defined as the 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [1] and implies three dimensions: environmental, social and in particular economic sustainability [2].

Today several research groups are working on the question how the environmental impact of the manufacturing and machine tools could be classified with reasonable metrics. This metric require a common and comparable base to set up an environmental and sustainable optimization and need to provide veridical information basis for the strategic management.

In order to make successful decisions in daily business, accurate information about business processes is very important. Therefore, an information system that provides performance figures of the business processes by simultaneously considering energy efficiency and performance aspects is seen as enabler for sustainable business development. By reason of its inherent complexity, such systems can never provide detailed information about all performance aspects. Too much information can lead to 'information overflow' for decision-makers. In order to reduce this complexity, Performance Indicators (PIs) are needed that give an overview of significant segments of reality.

## 2 STATE OF THE ART

Unfortunately neither machine tool builders nor manufactures have a clear picture of their actual resource- and energy consumption; therewith a universal evaluation metric for the environmental impact of machine tools is not existent. From an economic point of view, resources represent all value adding inputs, e.g. energy and materials, to fulfill a manufacturing process. Due to climate change and environmental reasons, stricter industrial requirements, especially automotive sector, costs and resource reasons in the context of green production as well as statutory requirements [3], energy efficiency has become a large research field.

### 2.1 Performance Assessment

In the past decades, manufacturing enterprises relied on performance measurement systems, which were based on traditional accounting systems to monitor and improve their operations [4, 5]. According to [6], it was shown that these systems do not cover the relevant performance issues of production. One significant limitation of traditional performance measurement systems is that they focus on controlling and reducing labour costs. However, labour cost currently constitute on average only 12% while overhead constitutes 50-55% of the manufacturing costs. Furthermore, the traditional systems are static and do not support neither the concepts of flexible lean production nor continuous improvement [6]. Gregory [7]

concludes in his state-of-the-art analysis of performance measurement systems for manufacturing companies that there is a need for a novel operations-based system which has the capability of evolving with the company.

## 2.2 Carbon footprint and energy efficiency

Moreover, global warming and increasing ecological awareness of the society force manufacturing companies to increase their energy efficiency at production as well as to respect the emerging new environmental regulations. The manufacturing industry is one of the largest consumer of energy and emitter of CO<sub>2</sub> [8]. The European Commission for example estimates an energy saving potential in the manufacturing sector of 25% [9]. Thus, assessing energy efficiency performance in production has become a major asset of manufacturing companies. Bunse [10] concludes in her gap analysis between the needs of the manufacturing industry and scientific literature that various energy efficiency performance measures already exist on aggregated sector or country level for analyzing the success or failure of policy initiatives. But that these performance measures are not necessarily suitable to assess energy efficiency performance of single manufacturing processes or single companies. In addition, manufacturing industry expressed the lack of appropriate energy efficiency metrics on machine, process and plant level and missing benchmarks dealing with energy efficiency and energy-profiles on machines and equipment. At the same time, emerging new sensor technologies and smart embedded devices enable operation-based process measurements and thus can provide accurate information for monitoring the production performance [11].

## 3 METHODOLOGICAL APPROACH FOR CO<sub>2</sub> EVALUATION

The herewith introduced methodology is applied for the evaluation of CO<sub>2</sub> emissions on a conventional machine tool. This bottom up approach is based on energy consumption measurement of the overall machine tool and its components to provide a reasonable ground for the CO<sub>2</sub> calculation. At first, each measured value (MV) from the data acquisition, e.g. components of the machine tool system, must be integrated over the considered timeframe. In a second step, these values are accumulated with other energies and transferred into a CO<sub>2</sub> equivalent ( $EV_{CO_2}$ ) to define a reasonable performance indicator for this application in the final step (**figure 1**).

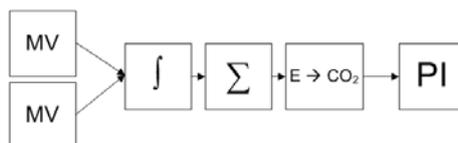


Figure 1: Methodology approach.

Furthermore this approach deals with restricted system boundaries, in more detail the machine tool and its auxiliaries, to get a complete and isolated picture of the individual machine tools' CO<sub>2</sub> emission (**figure 2**).

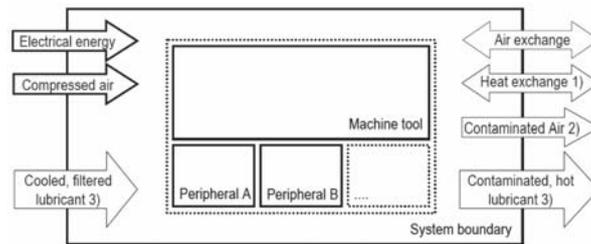


Figure 2: System boundary of the machine tool.

### 3.1 Requirements for the CO<sub>2</sub> emission evaluation of machine tools

Manufacturing systems, or more specifically machine tools, are very complex and designed to their individual applications. Compared to the CO<sub>2</sub> emissions evaluation of combustion engines, where clear defined chemical equations can be applied, in manufacturing, depending on the considered system boundaries, several energy inputs (e.g. electrical energy or pressurized air) must be comprised into the energetic balance. In many cases multiple relations and secondary effects, such as machine tool cooling and factory cooling, are given within a complex system. Furthermore multiple dependencies such as machine design, machine tool usage, quantity and quality of process- dependent and independent components define the energetic behavior of a manufacturing system and require an adequate measuring system.

Due to several possible energy forms and units, e.g. kWh, Joule and referring flow metering units such as Nm<sup>3</sup>/h for pressurized air, a common transformation unit must be applied. The applied transformation unit within this methodology is electrical energy in kWh, as it is the most dominant energy input in manufacturing, comprises high exergy and is used to generate the most applied auxiliary energies in manufacturing. The transformation factors are based on assumptions and benchmark values from literature. Due to the individual infrastructure of manufacturing systems and the focus on the system boundaries, the following approach is the most reasonable and comparable.

### 3.2 Data acquisition and definition of essential data

On the basis of the common conversion unit kWh and different energy inputs, the following data is necessary to provide a reasonable statement for a CO<sub>2</sub> consumption of a machine tool. This data is selected according to the fixed system boundary and the infrastructure of the given machine tool.

Electrical energy is represented by three major values: effective power, idle power and apparent output, all connected by the power factor  $\cos(\varphi)$ . For the CO<sub>2</sub> representation the effective power (kW) is taken into account as it indicates the effective work within the system. The share of inductivity and capacitance of each electric consumer leads to an asymmetric

dispersion of the high range of  $\cos(\varphi)$ . The data acquisition requires a refreshing rate of at least 5 Hz of the computed apparent output value to identify typical machining processes, e.g. start-up operations or change of  $\cos(\varphi)$ , and to guarantee a near-real-time data acquisition.

According to the system boundary, another often unnoticed energy input must be taken into account. Pressurized air is usually applied for sealing air, part and tool handling or process cooling. As pressurized air is generated in compressors and is in many cases responsible for the supply of the total production facility, flow- and pressure measuring on the machine tool must be applied. The applied technical unit for pressurized air consumption is  $\text{Nm}^3$  (standard cubic meter), according to DIN 1343. A multichannel measurement system according to [12] can fulfill these requirements.

### 3.3 Data acquisition and methodology to derive data

In correspondence with the defined system boundary (figure 2), the data is gathered independently from the compressed air generator. The transformation, from pressurized air mass flow to power output (in specific energy), is based on the following formula.

$$P(t) = C_1 \cdot \dot{m}(t) \quad (1)$$

A transformation factor, from standard cubic meters per hour ( $\text{Nm}^3/\text{h}$ ) to kilowatt hours (kWh) needs to be implemented, which includes also the energy losses of the compressor.  $C_1$ , with the value of  $6.5 - 7.5 \text{ kW}/(\text{m}^3/\text{min})$  [13] for compressed air transformation, multiplied by the mass flow from a calibrated flow measurement, provides the necessary transformation of the given system boundaries. The conversion factor  $C_1$  represents a benchmark value in efficiency within the industry sector. Therewith both the electrical energy and compressed air are transformed into a common energy equivalent unit and can be furthermore transformed with a  $\text{CO}_2$  emission factor.

### 3.4 Data acquisition and methodology to derive data

A universal carbon dioxide equivalent for electrical energy ( $EF_{\text{CO}_2}$ ) does not exist. Other than in chemical combustions, e.g. automotive sector, electrical power can be produced in many different ways with the result of different  $EF_{\text{CO}_2}$ . Nakata [14] points out multiple conversion factors, from  $740 - 1300 \text{ gCO}_2/\text{kWh}$ , due to different combustion procedures. Significant variances between numerous power plants, e.g. wind power plant with  $23 \text{ gCO}_2/\text{kWh}$  and brown coal power plant with  $1153 \text{ gCO}_2/\text{kWh}$ , show that the  $EF_{\text{CO}_2}$  is dependent not only on the combustion procedures but also from regional-dependant energy mixture. Therefore, information of the individual regional emission factors must be taken from official organizations and entities such as UBA [15], DEFRA [16] or WWF [17]. Summing up, the  $\text{CO}_2$  emission for the machine tool can be evaluated by the following formula:

$$EV_{\text{CO}_2} = \int_{t_1}^{t_2} P(t) dt \cdot EF_{\text{CO}_2} \quad (2)$$

The Emission value of CO<sub>2</sub> ( $EV_{CO_2}$ ) is defined by the integral of the effective power ( $P(t)$ ) multiplied by the individual regional carbon dioxide equivalent for electrical energy ( $EF_{CO_2}$ ).

### 3.5 Example measurement of a conventional turning lathe

The implementation of the above mentioned methodology is demonstrated for a typical hard turning machining process. To evaluate the CO<sub>2</sub> emission of this machine tool a typical reference process must be implemented according to machine tool energy measurements (table 1).

Data	Value	Unit
Duration	52	Sec
Cutting rate	150	m/min
Feed rate	0.15	mm/r
Cutting volume	3605	mm <sup>3</sup>
E consumption	0.106	kWh

Table 1. Conventional hard turning reference process.

The herewith measured reference process, which is a hard turning process on an automotive driveshaft, assigns the energetic behavior and therefore the  $EV_{CO_2}$  of the machine tool.

Taking the regional carbon dioxide equivalent  $EF_{CO_2}$  for the metropolitan area of Zurich Switzerland with 124g CO<sub>2</sub>/kWh an  $EV_{CO_2}$  of 13g CO<sub>2</sub> is emitted during one machining cycle.

### 3.6 Interpretation

This example shows how the CO<sub>2</sub> emission can be derived from a machine tool with various energy flows. According to the energy consumption data and other relevant machining information, CO<sub>2</sub> emission can be forwarded to an overall Manufacturing Execution System (MES). The given example further illustrates that the CO<sub>2</sub> output strongly depends on the applied  $EF_{CO_2}$ . Thereby the same machining process leads to different  $EV_{CO_2}$  in different assessment regions. This makes sense in an environmental impact evaluation as the regional energy production affects the environmental impact. It might be not suitable for an overall environmental impact comparison of the individual factory performance, as the only solution for an optimization of  $EV_{CO_2}$  is a machine tool- and process-independent location change or change in the energy supply. Therefore, two evaluation and indication goals can be pointed out:

1. The regional CO<sub>2</sub> emission impact caused by the location of the assessed machine tool.
2. The regional-independent environmental impact of different machine tools for the overall performance evaluation.

In the case of an overall ground factory performance evaluation (2), the regional  $EF_{CO_2}$  is not suitable. The calculated CO<sub>2</sub> emissions must be extended by additional machining process

information such as CO<sub>2</sub> consumption, which is dependent on cutting volume (CO<sub>2</sub>/mm<sup>3</sup>, e.g. roughing) or the CO<sub>2</sub> emission per machining hour (CO<sub>2</sub>/h<sub>m</sub>). A reasonable comparison of the CO<sub>2</sub> emission on machine tools must be based on a common EF<sub>CO2</sub> within this approach.

#### 4 CONCLUSION

In summary, due to the large variation observed among different EF<sub>CO2S</sub>, which are caused by regional consideration or energy mixture, and the poor correlation to the actual performance of the considered machine tool and machining process, CO<sub>2</sub> emissions (EV<sub>CO2</sub>) is not suitable as a performance indicator (PI) itself. The EV<sub>CO2</sub> in combination with machine processing time (EF<sub>CO2</sub>/h<sub>m</sub>) or process information, e.g. cutting volume (EV<sub>CO2</sub>/mm<sup>3</sup>) can be applied as a Performance Indicator for comparison if the regional factor remains unconsidered. The essential data acquisition and data handling can be adapted from the energy consumption measurement. Further investigations have to be done to detect and evaluate the emissions of CO<sub>2</sub> and other greenhouse gases for various energy forms or operations in manufacturing, such as the transportation and handling of the work piece or the thermal conditioning of the machine infrastructure.

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