Environmental evaluation of process chains

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Abstract

Environmental impacts of process chains have to be evaluated in order to be reduced. Over the last years, a number of models for environmental evaluation have been developed. However, their focus is on the product or the associated processes. The consideration of an entire process chain, including its productivity and the quantity of produced parts is not carried out. This article presents a new approach based on the overall energy demand, which extends the environmental evaluation of products by the productivity of process chains and provides a new key figure that enables an environmental evaluation and optimization of process chains.

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1. Introduction

1.1. Motivation

Referring to current environmental developments, the industry’s environmental responsibility has grown immensely over the last years due to its large energy share [1]. Here, planning and control of production processes play a major role, since a large part of the costs, but also of the required energy, are determined [2]. The selection and adjustment of process parameters in detailed planning and production control is of particular importance, as it has a decisive influence on the energy demand of a manufactured product [3]. However, the pure consideration of the energy demand of a product does not take into account the productivity of a process chain, e.g. in the form of idle times or scrap rate. A holistic environmental evaluation and optimization of process chains cannot be guaranteed this way [4].

This paper presents an approach that enables a holistic environmental evaluation of process chains developed on the basis of the overall energy demand. With help of a newly developed indicator, which is based on key performance and key environmental indicators (KPI, KEI), the simultaneous evaluation and optimization of products and process chains can take place.

1.2. Scope and Structure

The developed approach refers to machining processes, but can also be easily adapted to other manufacturing processes. Based on this scope, the current state of the art is presented. The following development of the approach results from the deficiencies identified here. The approach is then examined exemplarily for applicability. The identification of further contents concludes the paper.

2. State of the Art

The developed approach is to be used in detailed planning as well as in production control. For this reason, the tasks and contents as well as the objectives of detailed planning and production control will be explained in more detail below. Since the energy demand is an integral part of the new approach, the assessment will then be described in more detail based on the overall energy demand.
2.1. Detailed planning and production control

Detailed planning is a phase of production planning, which comprises all initial planning activities that are carried out in order to manufacture a product according to defined objectives (see Chapter 2.2.). The individual phases and activities can be seen in Fig. 1. The subsequent production control serves to realize the planned production schedule. This includes monitoring of e.g. quality and a needs-based readjustment in case of sudden changes and disturbances, like production downtimes. [5]

Rough planning entails decisions about investments, production technologies and process chains based on a determined production schedule. The production equipment is chosen according to the products to be manufactured. For a machining process, this means selecting of machine tool, clamping system and tool concept. Detailed planning means the product-related determination of process parameters like spindle speed, feed rate and depth as well as the amount of cooling lubricant, which in turn have a direct influence on the energy demand [6,5]. If disturbances or exceedances of defined tolerance limits occur, e.g. with regard to tool wear, the production is readjusted. This includes the adaption of process parameters as well as the rescheduling of resources [5].

2.2. Objectives and evaluation indicators

The selection of process parameters during detailed planning and production control is based on defined objectives, whose focus is typically on cost-effectiveness. Maximum and balanced capacity utilization, maximum quality, minimum throughput times, keeping delivery dates and low inventories are the main objectives [7]. The achievement of these objectives can be measured using key performance indicators (KPI). Typical KPI here are scrap ratio or set-up times [8].

These are merely economic objectives. Environmental objectives, like minimum energy demand, are considered separately. Key environmental performance indicators (KEI), e.g. the total energy demand, the global warming potential or human toxicity, are the basis of the evaluation [9]. Energy demand is of particular importance here, as it can be controlled by setting process parameters accordingly. It also offers the possibility of considering resource requirements based on the overall energy demand.

2.2.1. Evaluation of overall energy demand

Several approaches for the evaluation of the overall energy demand exist. The most important approaches are the cumulative energy demand (CED) and the embodied energy approach. The approaches are similar, but have different system boundaries. While the cumulative energy demand considers all processes from the production to the disposal of a product [10], the embodied energy approach only considers the production of the good [11] and, thus, is a component of the CED.

The CED is the sum of individual energy demands resulting from various material flows within defined system boundaries. A process chain consists of a number n of processes P [6]. A process begins with its upstream and ends with its downstream processes (UPi-p and DPi-p) as shown in Fig. 2.

In case of a machining process, upstream processes contain the supply of raw material as well as the supply and production of cooling lubricant and tools. In turn, downstream processes contain the recycling and dispose material, cooling lubricant and tools. This results in the following CED based on the main results of [12–17]:

\[
CED = E_M + E_{CL} + E_T + E_{WM}
\]  
(2.1)

The energy demand of the machining operation is represented by \( E_M \), the energy demand caused by the mass \( m_{CL} \) of cooling lubricant applied by \( E_{CL} \), the energy demand entailed by the mass \( m_T \) of tools used by \( E_T \) and \( E_{WM} \) represents the amount of energy caused by the fabricated workpiece material \( m_{WM} \). The energy demand of the machining process \( E_M \) can be further detailed according to [12,14–16]:

\[
E_M = E_{Standby} + E_{Spindle} + E_{Feed} + E_{Cut}
\]  
(2.2)

The term \( E_{CL} \) has to be defined further according to attached production (\( E_{pPCL} \)), reprocessing (\( E_{pPCL} \)) and recycling (\( E_{pCL} \)) processes as well as the energy demand for the supply itself (\( E_{sCL} \)) [17].
These additional energy demands are calculated using the $CED_{CL}$ of the cooling lubricant:

$$E_{CL} = E_{RCL} + E_{RFCL} + E_{RCL} = CED_{CL} \cdot m_{CL} \quad (2.3)$$

The same applies to the energy demand of the used tool with $E_{CT}$ as energy demand caused by tool change, $E_{PT}$, $E_{RPT}$ and $E_{RT}$ caused by production, reprocessing and recycling of the tool [17].

The $CED_{T}$ of the tool summarizes the energy demands:

$$E_{T} = E_{PT} + E_{RPT} + E_{RT} + E_{CT} = CED_{T} \cdot m_{T} \quad (2.4)$$

$E_{WM}$ is composed similarly with $E_{MWM}$ as the energy demand for the raw material mining and supply and $E_{RWM}$ as recycling energy demand [17]. The $CED_{WM}$ of the workpiece material combines the energy demands:

$$E_{WM} = E_{MWM} + E_{RWM} = CED_{WM} \cdot m_{WM} \quad (2.5)$$

In case of several processes, the individual components of Eq. 2.1 can be totaled up. If a number $n$ of processes has to be considered, $E_{M}$, $E_{CL}$, $E_{T}$ and $E_{WM}$ are summed up and added accordingly, s. Eq. 2.6:

$$CED = \sum_{i=1}^{n} E_{M,i} + \sum_{i=1}^{n} E_{CL,i} + \sum_{i=1}^{n} E_{T,i} + \sum_{i=1}^{n} E_{WM,i} \quad (2.6)$$

The $CED$ only contains information about one product passing several processes. However, several processes build a process chain. Eq. 2.6 clearly shows that interdependencies between the processes in form of the productivity of the process chain e.g. in terms of idle times or quality losses is not taken into account. Therefore, an environmental evaluation based on the energy demand of process chains is not possible. Thus, environmental impacts of process chains are not considered during detailed planning and production control.

3. Environmental evaluation of process chains

As depicted in Chapter 2, an approach, which enables the environmental evaluation of process chains, is needed. Therefore, an indicator is developed, which extends the product related $CED$ by the productivity of a process chain. This indicator is then integrated into detailed planning and production control. The applicability is evaluated using an exemplary process chain. Finally, the integration into a software system is presented.

3.1. Development of an environmental indicator

To enable the environmental evaluation and optimization of process chains, the productivity of process chains has to be considered. In line with the overall equipment effectiveness (OEE) [8], the productivity is assessed based on quality and capacity utilization. The scrap rate ($SR$) is selected as KPI for quality, the capacity utilization is assessed on the basis of idle times. The combination of productivity and CED as well as the consideration of a number $m$ of produced products results in the following indicator $CED_{PC}$:

$$CED_{PC} = (1 + SR) \left( \sum_{i=1}^{m} CED_{i,j} + \sum_{i=1}^{n} E_{i,j} \right) \quad (3.1)$$

The $CED_{PC}$ quantifies the overall energy demand of a process chain with $n$ processes and $m$ processed products. The term in the brackets represents the individual energy demand of a product running a process chain with $n$ processes including idle times, like set-up or production downtimes ($E_i$). By adding up the individual product-related energy demands, the total energy requirement for $m$ products is calculated, which is then multiplied by the $SR$. This way, the overall energy demand of the entire process chain can be determined. By dividing the $CED_{PC}$ by the number of products $m$, a product related $CED_{PPC}$ is obtained that is averaged over the process chain, s. Eq. 3.2:

$$CED_{PPC} = \frac{1}{m} \left( (1 + SR) \sum_{i=1}^{m} \left( \sum_{i=1}^{n} CED_{i,j} + \sum_{i=1}^{n} E_{i,j} \right) \right) \quad (3.2)$$

The $CED_{PPC}$ can be used to evaluate and optimize process chains and products in holistic terms. By comparison of planned and actual values, optimization potentials can be identified. To exploit the identified optimization potentials, the design of the individual processes can be optimized, processes exchanged or the productivity improved.

3.2. Integration into detailed planning and production control

The design of the processes is part of the detailed planning. By optimizing the processes, the term $CED_{i,j}$ of Eq. 3.2 can be minimized. Therefore, process parameters are selected accordingly. In case of a machining process this means the adjusting of spindle speed, feed rate and depth of cut. The calculation uses planning data, e.g. from CAD, MES or ERP.

The subsequent production control aims at maximizing the productivity with the help of maximum capacity utilization and minimum scrap rate. Thus, the term $E_{i,j}$ and the factor $(1 + SR)$ can be minimized based on feedback data replicated from production in real-time. Fig. 3 shows the relations graphically.

![Fig. 3. KEPI-based detailed planning and production control.](Image 318x81 to 531x107)
Possible measures in the context of production control would be, for example, continuous quality monitoring and the corresponding identification of critical points. In order to reduce idle times, setup processes can be optimized and production leveled in order to avoid waiting times. The replicated data out of production are of great importance here, e.g. the real-time visualization of machine occupancy.

3.3. Case study: evaluation of a process chain

The developed CED_{PPC} approach has to be detailed according to the processes of the process chain. To guarantee the applicability, a sample calculation is carried out on the basis of an exemplary process chain consisting of a forming process followed by a turning process. The energy of the fabricated material and tool changes are not considered in this example. First, the CEDs of the processes are calculated. For the forming process an energy demand of CED_{Forming} = 0.5 kWh and an idling power demand of 4 kW are assumed. By specification of Eq. 2.1, the energy demand of the turning process is determined by the following equations [16]:

\[
CED = CED_{CL} \cdot q_L \cdot t_c + P_{\text{Lubpump}} \cdot t_c
\]

\[+CED_T \cdot m_T \cdot \left(\frac{t_c}{T_T}\right) + P_M \cdot t_c \quad (3.3)
\]

with \( P_M \) as machining power consisting of:

\[
P_M = P_{\text{Standby}} + (k_n \cdot n + b) + (k_f \cdot f + c) + SEC \cdot MRR
\]

\[+SEC \cdot MRR \quad (3.4)
\]

and \( MRR \) after:

\[
MRR = a_p \cdot f \cdot v_c \quad (3.5)
\]

and \( T_T \) as the machine tool life after Taylor:

\[
T_T = \frac{A}{v_c^{1/\alpha} \cdot f^{1/\beta} \cdot a_p^{1/\gamma}} \quad (3.6)
\]

Furthermore, the energy required by idle times can be calculated by Eq. 3.7:

\[
E_I = P_{\text{Standby}} \cdot t_I \quad (3.7)
\]

For the calculation, the following parameters are chosen, s. Table 1 and Table 2. Table 1 lists the parameters of the turning process:

Table 1. Parameters for a turning process (based on [13,16] and assumptions).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponents in tool life equation</td>
<td>1/\alpha; 1/\beta; 1/\gamma</td>
<td>5.63; 0; 0</td>
<td></td>
</tr>
<tr>
<td>Constant in tool life equation</td>
<td>A</td>
<td>5.25 \times 10^{14}</td>
<td></td>
</tr>
<tr>
<td>Depth of cut</td>
<td>a_p</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Specific coefficient of spindle motor</td>
<td>b</td>
<td>0.5</td>
<td>kW</td>
</tr>
<tr>
<td>Specific coefficient of feed motor</td>
<td>c</td>
<td>0.1</td>
<td>kW</td>
</tr>
<tr>
<td>CED of cooling lubricant</td>
<td>CED_{cl}</td>
<td>1.37</td>
<td>MJ/kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CED of tool</td>
<td>400</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Feed</td>
<td>0.15</td>
<td>mm</td>
</tr>
<tr>
<td>Specific coefficient of feed motor</td>
<td>0.88</td>
<td>W/mm</td>
</tr>
<tr>
<td>Specific coefficient of spindle motor</td>
<td>3.74</td>
<td>W/mm²</td>
</tr>
<tr>
<td>Tool weight (assumed)</td>
<td>10</td>
<td>g</td>
</tr>
<tr>
<td>Spindle speed (assumed)</td>
<td>1991</td>
<td>min⁻¹</td>
</tr>
<tr>
<td>Lubrication pump power demand</td>
<td>0.6</td>
<td>kW</td>
</tr>
<tr>
<td>Standby power demand</td>
<td>4.5</td>
<td>kW</td>
</tr>
<tr>
<td>Consumption of cooling lubricant</td>
<td>7.92 \times 10^{-3}</td>
<td>kW/min</td>
</tr>
<tr>
<td>Specific energy consumption</td>
<td>3.3</td>
<td>J/mm³</td>
</tr>
<tr>
<td>Actual cutting time (assumed)</td>
<td>5</td>
<td>min</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>125</td>
<td>m/min</td>
</tr>
</tbody>
</table>

The process chain related parameters are assumed as follows:

Table 2. Parameters of the process chain.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap rate</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Idle time turning</td>
<td>0.5</td>
<td>min</td>
</tr>
<tr>
<td>Idle time forming</td>
<td>1</td>
<td>min</td>
</tr>
<tr>
<td>Number of products</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

By inserting the parameters in Eq. 3.1 to 3.7 the following results are obtained:

Table 3. Calculation results.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Reference</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CED_{Turning}</td>
<td>Product</td>
<td>1.16</td>
<td>kWh</td>
</tr>
<tr>
<td>CED_{Forming}</td>
<td>Product</td>
<td>0.5</td>
<td>kWh</td>
</tr>
<tr>
<td>E_I_{Turning}</td>
<td>Product</td>
<td>0.038</td>
<td>kWh</td>
</tr>
<tr>
<td>E_I_{Forming}</td>
<td>Product</td>
<td>0.067</td>
<td>kWh</td>
</tr>
<tr>
<td>CED_{PPC}</td>
<td>Product</td>
<td>92.66</td>
<td>kWh</td>
</tr>
<tr>
<td>CED_{PPC}</td>
<td>Product</td>
<td>1.85</td>
<td>kWh</td>
</tr>
</tbody>
</table>

To manage the CED_{PPC} (and thus the CED_{PPC}), process parameters can be adjusted by detailed planning, processes can be exchanged or the productivity can be improved by production control.

The productivity can be increased by reducing idle times and scrap rate with the help of production control, s. chapter 3.2. In this example the energetic part of idle times and scrap rate accounts for 11%. If idle times are reduced by 50% the CED_{PPC} is decreased by 3%, the energetic component caused by the productivity losses is reduced by 30%.

The adaptation of the process parameters by detailed planning causes changes in the machining time, tool wear and cooling lubricant supply. Higher process parameters for example lead to reduced production times and thus maximized productivity and a lower machining energy demand (considering \( P_{\text{Standby}} \)), if the machines are shut down during non-production
times. However, this is not carried out in praxis due to thermal effects and long set-up-times. In addition, a negative influence on quality cannot be ruled out. As a result, high actuating values lead to a fluctuating load that causes the energy demand to rise. On the other hand, lower actuating values result in lower process temperatures and thus a higher tool life, less component distortion and cooling lubricant demand. However, production time and thus the time of cooling lubricant supply increases. Furthermore, the productivity decreases. As can be seen, versatile dependencies, which contradict each other, exist. These contradictions lead to an optimization problem, which can no longer be solved manually. If real-time influences from machining are also to be taken into account to enable integrated production control, a software solution is indispensable to solve this multi-criteria optimization problem.

3.4. Software tool: The virtual planner

To solve this optimization problem the virtual planner, a software tool developed at the IFW, is used. The virtual planner enables the illustration of the production, especially the machine occupancy, in real time for integrative production planning and control [18].

This software tool has to be extended by interfaces for real-time data acquisition, like machine tool energy demand, flow of cooling lubricant or tool wear. In case of sudden disturbances such as machine failures, these data help to determine optimized process parameters with help of the CEDPPC approach.

In addition to these interfaces, the tool requires a connection to databases containing CED values of cooling lubricants and tools. These databases are currently being built up. Data for cooling lubricants are identified with help of detailed literature research and expert interviews. The database of tools is developed together with a well-known tool manufacturer.

Using these data and determined dependencies, an algorithm is developed that is capable of setting optimal process parameters and, in the case of sudden disturbances, of determining new process chains and process parameters based on real-time data.

4. Summary and outlook

Environmental impacts of process chains must be taken into account when making decisions in detailed planning and production control. Purely considering economic Objectives leads to a lack of sustainability and to drastic consequences for the environment. To solve this issue, an indicator has been developed, which combines the environmental evaluation of products and process chains into one indicator – the CEDPPC. The CEDPPC links the CED of a product and the productivity of a process chain in form of SR and idle times. Based on this, process parameters are then determined in detailed planning and the process chain productivity is optimized in production control to minimize the CEDPPC.

The applicability of this approach was examined by a calculation based on sample data. Optimization potentials could be derived from these calculation, which, however, cannot be solved manually due to their complex interactions. Therefore, a software solution was presented which is supposed to carry out the calculations explained as well as the objective-oriented selection and adjustment of the process chain and its process parameters. By applying this approach, an environmental evaluation based on the overall energy demand of process chains is possible.

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References