Machine tool optimization strategies for ecologic and economic efficiency

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1 INTRODUCTION

As manufacturing costs can be globally identified and assigned, and resources for manufacturing on shop-floor level, e.g. energy, can be identified and directly assigned to their consumers as well, both approaches in combination can be used to determine potential fields of action for the energy efficiency improvements. Knowledge of energy consumption is mandatory for optimization and is requested for the development of further machine tool energy consumption models. Referring to the manifold assessment levels as introduced by Dornfeld [1] this assessment and evaluation pertains to the subcomponents of a machine tool.

Multiple measurement initiatives, e.g. Duflou [2], and own machine tool power measurements with subsequent power data analysis [3], can provide a clear picture of a machine tool’s energy and resource consumption behaviour. Unfortunately, today, this ability is very uncommon in the industrial environment and on the subcomponent level. The ability to determine design features, based on evaluations that have influence on both, the energy consumption and investment, is an important aspect of competitiveness and improvement in the future and might also become mandatory due to EU legislation [4].

Manufacturing and machine tool operational information and interpretation of this data, is mandatory for a reasonable prediction of the energy consumed and eventual design changes. Vague information could lead to false or ineffective investment strategies. For instance, a machine tool that is used in a three shift work pattern requires different optimization actions and retrofit solutions from machine tools for occasional use on the shop-floor level. One main reason for those differing optimization activities are key performance indicators, e.g. the effectiveness, the value-add and non-value-add usage ratio of the machine tool components in various machining processes. This can be understood as an approach of an Overall Equipment Effectiveness (OEE) on the machine tool component level.

2 STATE OF THE ART

In principle, sustainability can be addressed with two approaches, a top-down approach with an estimative, indicative and quantifying characteristic, addressing general assessment level, e.g. Life Cycle Assessment (LCA) [5], and a bottom-up approach, addressing detailed assessment levels, such as energy assessment on subcomponent and process level [6]. Immediate optimization activities can be directly identified and addressed at the subcomponent and process level following a bottom-up assessment approach which is more effective. This approach is introduced by this paper.

Retrofit in combination with service and repair, longevity of the product and replacement is seen as a potential technical and economic field of action. An internal study among Swiss SMEs discloses an unknown and underestimated potential for retrofit solutions. Retrofit, meaning the change or exchange of subcomponents is recognized as a potential energy and waste saving activity [7]. More than twenty companies in Japan, which specialize in retrofit, refurbishment and remanufacturing activities, e.g. Okuma Corporation, endorse the environmental and economic potential for those activities in the industry [8]. Weule [9] and Weyland [10] point out the ecologic and economic potential of the re-use of peripheral systems. Kirchner [11] and own measurements [12] ascertain that machine tools are often not designed according to energy consumption criteria, mainly due to the peripheral design and the inter-peripheral adjustment. In retrofitting, the challenge remains the
selection of appropriate solutions, that are at the same time economic, and ecologic.

The focus within this research is the detection and evaluation of potential retrofit activities particularly in peripheral equipment whereas the process zone and its needs remains unquestioned. This focus is preferred according to [11, 2] and because measurements show that there is less potential for optimization for inner process related components, e.g. controls.

In most cases, the use phase of machine tools is expected to be more than ten years [13], thus retrofit and refurbishment must be considered not only for maintenance and service reasons but also for continuous improvement during machine tool usage. The goal, along with the herewith presented research work, is to propose a method to identify the most reasonable measures for the improvement of energy efficiency by retrofit and to evaluate its return on invest.

3 METHODOLOGY

3.1 Retrofit indication

The methodology is represented by four steps. Heuristically, process supporting components should adapt continuously their power consumption to the intensity of the process, more precisely, to the variation of process parameters. It is therefore assumed that supporting function, e.g. cooling, should be fluctuating as well. This approach is based on two major technical aspects that are considered as indication for the energy efficiency of a machine tool component:

- **Energy consumption of the machine tool component**: Components with a high share of the overall energy consumption are assumed to also have a high saving potential.
- **Mode of operation**: Open loop controlled components are assumed to have a higher potential for efficiency improvement than closed loop controlled components.

Combining these values represents an indicator for potential retrofit $h_k$, defined by

$$ I_R = A_E \cdot A_O $$

with $A_E$ [-] representing the power share of one component during operational state of the total and $A_O$ [-] as a weighting factor, representing the mode of operation of the component. $A_O \approx 1$ represents an ideal constant energetic behavior, and $A_O \approx 0$ represents an alternating, variable energetic behavior.

3.2 Methodological steps

**Step 1 – Detailed machine tool measurement**

A detailed effective power measurement and assessment is mandatory, most suitably by a multichannel measurement system to gain coherent data from all active machine tool components. The machine tool measurement and assessment includes several subtasks:

- **Definition of appropriate system boundaries**: that include all relevant peripherals and all relevant energy forms as in- and outputs to and from the system boundaries simultaneously.
- **Definition of operation states and definition of shift regime**, i.e. sequence of operating shifts, observation period and use scenario for the given machine tool environment.
- **Definition of a reference process for the operation state “machining”**: which exploits the capabilities of the machine tool and defines a basis for optimization.
- **Listing of all relevant costs that are represented by fixed and variable costs within the total costs for relevant machine tool components.**

As the energetic behavior of the components depends on environmental and infrastructural constraints, e.g. thermal state or process duration and frequency, a simultaneous measurement is recommended [12].

**Step 2 – Calculation of retrofit indicator $h_k$**

For each machine tool component, the retrofit indicator $h_k$ must be determined by individual measurements during the observation period, where the period is subdivided by sampling intervals of length $t_{sample}$. As the measurement consists of discrete effective power values, the energy share of each component $i$, $A_{E,i}$ is calculated in equation (2):

$$ A_{E,i} = \frac{E_i}{E_{System}} \cdot \frac{\sum_{j=0}^{n} P_{i,j}}{\sum_{j=0}^{n} P_{System,j}} $$

with

$$ n = \frac{t_{total}}{t_{sample}} $$

$E_i$ [kWh]: energy supplied to component $i$ during observation period.
$E_{System}$ [kWh]: energy supplied to machine tool, accordingly to system border definition.
$P_{i,j}$ [W]: effective power of each component $i$ at sampling point.
$P_{System,j}$ [W]: total effective power of machine tool, according to system border definition at sampling point.
$n$ [-]: number of samples within observation period $t_{total}$.
$t_{total}$ [s]: observation time variation of process parameters.
$t_{sample}$ [s]: length of sampling interval.

The operational mode of the component, $A_O$ is calculated by an occurrence frequency evaluation of the measured effective power values.

A component is considered as process-independent if it has at all sampling points the same power. Components with a close loop controlled energetic behavior are represented by more different energy levels. Therefore a parameter to indicate the fluctuation of a component’s power supply needs to be defined. This information can then be used as an indication for the component effectiveness, as mentioned above. Due to high value fluctuation, the application of mathematical variance calculation is not sufficient for the evaluation of the mode of operation, taken from an effective power measurement. Other methods, e.g. rainfall or time at level counting [14] were investigated and reviewed for this application. An analysis of available evaluation methods, to
determine the constancy of values within measurements, and performed experiments revealed that this occurrence frequency evaluation fulfils the analysis requirements to the full extent through a clear and easy-to-read statement.

In this given approach a definition of classes, as it is mandatory within a time at level counting, is not needed due to a direct value counting procedure. The calculation of $A_0$ can be described in 4 steps:

**Value transformation**

The measured discrete values $P_i$ must be transformed with the lowest global value $P_{\text{min,global}}$ in order to provide $P_{\text{trans}} \geq 0$ values for further accumulation and comparability among the components. The transformation, given by an origin of coordinates shifting, is done by equation (4):

$$P_{i,\text{trans}} = P_i - P_{\text{min,global}}$$  \hspace{1cm} (4)

$P_{i,\text{trans}}$ [W]: Transformed effective power of each component $i$.

$P_i$ [W]: Effective power of each component $i$ during the observation period.

$P_{\text{min,global}}$ [W]: Lowest global value within the observation period.

**Normalized values**

To provide a comparison among all evaluated machine components, $P_{i,\text{trans}}$ must be normalized with the global maxima according to equation (5). This calculation is done for each component.

$$P_{i,\text{norm}} = \frac{P_{i,\text{trans}}}{P_{i,\text{max,global}} - P_{i,\text{min,global}}}$$  \hspace{1cm} (5)

**Sort values**

As the measured values are transformed and standardized by the global limit values, the $P_{i,\text{norm}}$ must be sorted in descending order. The sorting can be performed either in descending or ascending order, for practical reason descending order is chosen. The sort-value distribution describes a cumulative frequency distribution.

Fig.1 shows the standardized $P_{i,\text{new}}$ values (black line) with the resulting value sorting represented by the dotted line.

**Regression line**

The cumulative frequency distribution is dissolved equidistantly in abscissa direction but not in ordinate direction. To maintain a equal weighting of both axes, the cumulative frequency distribution is sampled along the path with a length increment $L_{\text{inc}}$ [•] represented in equation (6):

$$L_{\text{inc}} = L_{\text{total}} \left( \frac{n}{(n-1)} \right)$$  \hspace{1cm} (6)

$L_{\text{inc}}$ [•]: Incremental length of supporting points.

$L_{\text{total}}$ [•]: Total length of sum-level-duration plot.

$n$ [•]: Number of samples within observation period $t_{\text{total}}$.

Finally, the gradient of a regression line through the allocated points quantifies the dimension of the operational mode of each consumer. The weighting factor $A_{OI}$ is calculated according to:

$$A_{OI} = \frac{45\degree - \varphi_i}{45\degree}$$  \hspace{1cm} (7)

$\varphi_i$ [°]: Inclination angle of the regression line.

**Step 3 – Determination of retrofit activity**

The evaluation of a retrofit indicator can now be applied to specify concrete fields of action for optimization. Herewith a list from the calculated retrofit indication is given in descending order. Consumers with the highest retrofit indicator value should be considered and approved for
potential retrofitting activities with priority. Retrofit and refurbishment activities are dependent on:

- impact on the process stability and quality, and relevance
- technical and operating expense for retrofit.
- economic considerations and payback.

The following retrofit measures can be considered, sorted by increasing complexity:

a) turn off component, if applicable
b) apply adjusted control or reduced duty
c) replace component by a more efficient one
d) replace subsystem while providing same function
e) combinations of a to c

The technical retrofit and refurbishment determination activities have to be considered under effectiveness and efficiency aspects. Referred to EN ISO 9000:2005 efficiency is defined as the relationship between the results achieved and resources used. As the energetic input is quantifiable, however the output is not, the produced part has to remain constant in order to allow comparison. Thus retrofit activities follow the minimization principle and the efficiency of the machine tool should be considered for the determination of any optimization activities.

**Step 4 – Evaluation of retrofit activity**

Within this research several influence factors within the cost evaluation in manufacturing were assessed, resulting, that Total Cost of Ownership (TCO) and Life Cycle Cost (LCC) represent the most valuable approaches, whereas both approaches, also due to the current relatively low energy price, neglect energy consumption but are applicable on the component level.

The technically selected retrofit activity has to be evaluated pursuant to the economic goals of the user. More advanced industrial fields, e.g. building technologies, apply several energy related economic investment evaluation methods [15].

The following parameters can be pointed out as the most critical influences on economic goals:

- usage of machine tool and its components
- lifetime and maintenance of the machine tool and its components

The presented method is built on four major evaluation steps as represented by the process chart in fig. (3).

![Process chart for economic evaluation.](image)

The objective in using the TCO calculation within this evaluation method is to assign all relevant costs for further calculations. These costs can be divided into fixed costs, such as initial costs, rebuilding, refurbishment and recycling costs, and variable costs, such as costs for maintenance, costs of operation, and energy costs. Equation (8) represents the calculation of the relevant costs within retrofitting.

\[ C_o(t) = \sum_i (F_i + F_i \cdot C_e \cdot U_E + C_M \cdot t) \]

- \( C_o(t) [-]\): linear cost function of the component.
- \( F_i [\text{CHF}]\): fixed costs of the component.
- \( C_e [\text{CHF/kWh}]\): price per kWh.
- \( U_E [\text{kWh/t}]\): usage of machine tool component
- \( C_M [\text{CHF/t}]\): maintenance costs per time.

On the basis of a TCO calculation and provided that the relevant costs are known and assigned, a static break-even analysis can be performed. This method compares the occurred costs for retrofitting with the existent cost of the component along the presumed and existent usage and energetic behavior within individual time frames. The machine tool usage (Fig. 4) reveals the operating states of each component, its duration and type, e.g. cycle-time (tC) or machine set-up time (tS).

![Measured usage of machine tool.](image)

The applied method and equation (8) reveals the influence of the most critical parameters in the evaluation of ROI that are represented by the 1) machine tool usage, 2) fixed costs of the component and 3) the price per kWh in descending order. Whereat 2 remains unchanged, 1 and 3 will are variable change.

As tendencies of rising energy prices are very likely [16] the critical parameter of energy price will gain importance.

Fig. 5 shows the results of a Static Break-Even Analysis on the basis of a retrofitted hydraulic accumulator compared to a standard hydraulic pump system with the usage of a given machine tool usecase, represented by fig. (4).
Conditioned by the fact that the present value of the monetary investment is neglected in this static evaluation, the Net Present Value (NPV) is applied as an additional criteria. According to Warnecke [17] and Seiler [18] it is only applicable for the comparison of projects with the same initial investment. Seiler [18] also points out that NPV can be also valid for projects with different initial investments if their difference is known and a negative or positive NPV can be calculated. According to the given evaluation requirements, this modification of the NPV is represented by:

\[
NPV = -I_0 + \sum_{t=1}^{T} \frac{D_t}{(1+i)^t} + D_{tD} + (1+i)^{-T} \cdot \frac{I_R}{i}
\]  

\(I_0\) [CHF]: Difference between evaluated investments.
\(T\) [y]: Expected remaining time of use.
\(D_t\) [€]: Difference of the variable costs.
\(i\) [%]: Required rate of return, here 8%

\(D_t\) can be determined from the usage of the machine tool components by:

\[
D_t = -(C_0 \cdot U_{EA} + C_{MA}) + (C_0 \cdot U_{EB} + C_{MB})
\]

\(C_0\) [CHF/kWh]: Price per kWh.
\(U_{EA,B}\) [kWh/t]: Usage of machine tool component A or B.
\(C_{MA,B}\) [CHF/t]: Maintenance costs of component A or B.

The presented retrofit and refurbishment evaluation shows the combination of technical and economic approaches. The developed methodology was applied on use cases of different machine tools, including a conventional lathe for verification.

4 VERIFICATION OF METHODOLOGICAL APPROACH

4.1 Detailed machine tool measurement

Due to extended machine measurements and efficiency and effectiveness assessments, the following example can be pointed out to verify the retrofit indication with the developed calculation methodology. Tab. 1 shows a reference process applied on a lathe with a two axis tool positioning system, dry processing and compressed air process cooling.

### Tab. 1: Reference process

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>340</td>
<td>s</td>
</tr>
<tr>
<td>Cutting rate (max)</td>
<td>150</td>
<td>m/min</td>
</tr>
<tr>
<td>Feed rate (max)</td>
<td>0.15</td>
<td>mm/r</td>
</tr>
<tr>
<td>Cutting volume</td>
<td>3605</td>
<td>mm³</td>
</tr>
</tbody>
</table>

The reference process, is defined as a typical machine tool process that represents a typical application of the designed machine tool. In the present example, a hard turning process of an automotive pinion is applied.

The machine tool usage is represented by Fig. 4. Additional measurements of operational modes can be performed according to assigned scenarios. The observation period for this example is defined by the four similar cycles including set-up-times and result to a total observation time of \(t_{total} = 340\) s.

4.2 Calculation of retrofit indicator \(I_R\)

The total machine tool measurement revealed the following top-five retrofit indication information for each measured consumer before the retrofit optimization shown in Tab 2.

### Tab. 2: Resulting retrofit indication

<table>
<thead>
<tr>
<th>Consumer</th>
<th>(A_0) [-]</th>
<th>(A_o) [-]</th>
<th>(I_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed air</td>
<td>0.321</td>
<td>0.638</td>
<td>0.205</td>
</tr>
<tr>
<td>Cooling fan</td>
<td>0.153</td>
<td>0.989</td>
<td>0.153</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>0.109</td>
<td>0.989</td>
<td>0.107</td>
</tr>
<tr>
<td>Cooling pump 1</td>
<td>0.100</td>
<td>1.000</td>
<td>0.100</td>
</tr>
<tr>
<td>CNC Total</td>
<td>0.193</td>
<td>0.359</td>
<td>0.069</td>
</tr>
</tbody>
</table>

4.3 Determination of retrofit activity

The performed assessment revealed that the process and machine tool cooling, as well as the hydraulic system should be investigated in more detail for potential retrofit solutions. As the machine tool and process cooling directly influences the machining process, the investigations are focused on an auxiliary system, the hydraulic system.

In the given case the hydraulic is used to open and lock the chuck for the workpiece clamping.

According to the given retrofit definition and the possible retrofit activities the further evaluation bases on the replacement of the current hydraulic system by a hydraulic pump combined with a hydraulic accumulator system.

Fig. 6 shows as comparison to fig. 4 the results of the measurement after the selected retrofit action. It shows the results of effective power measurements according to the given reference process. In the following case the application of a hydraulic accumulator reveals a total effective power saving of 96% on the hydraulic system and an overall power saving of 12% on the machine tool.

As during evaluation the effective power output is not known, manufactures’ instructions and white sheets have to be considered.
component and joint costs for retrofit and refurbishment. This method is considered a promising assessment with two goals in sustainability within manufacturing. It relies on a combined approach, technical and economic, to achieve a clear input, the effective power measurement, corresponding components, cost and investment structure.

Furthermore simulation activities and awareness for next generation machine tools can be based on the findings. Due to possible EU regulation and a positive effect on the ecological footprint [6], retrofit and refurbishment activities should be considered as a potential field of actions for a holistic sustainable manufacturing approach.

6 ACKNOWLEDGMENTS

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7 REFERENCES


4.4 Evaluation of retrofit activity

For the economic evaluation of the selected retrofit activity the following cost structure shown in table 3 is taken into account.

Tab. 3: Cost parameters of hydraulic accumulator

<table>
<thead>
<tr>
<th>Cost type</th>
<th>Purpose</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fix costs</td>
<td>Material</td>
<td>1559 CHF</td>
</tr>
<tr>
<td></td>
<td>Setting up</td>
<td>1435 CHF</td>
</tr>
<tr>
<td>Variable costs</td>
<td>Disposal</td>
<td>0 CHF</td>
</tr>
<tr>
<td>Variable costs</td>
<td>Service</td>
<td>500 CHF/a</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>0 CHF/a</td>
</tr>
<tr>
<td></td>
<td>Energy price</td>
<td>0.147 CHF/kWh</td>
</tr>
</tbody>
</table>

Due to the investment cost to energy price ratio longer payback times should be considered in the application of retrofitting in manufacturing. In the following case the return on investment is reached after seven years (fig. 5). Under the presumption of a machine tool life time of twenty years and a required return rate of eight percent in the following example with a minimal positive NPV of results in 1848 CHF.

5 CONCLUSION

According to the given use case, as well as the machine tool system design, the retrofit indication determined and ranked potential retrofit fields of action. It indicates technical weak points that can be directly evaluated with the given economic evaluation strategies.

The herewith presented economic evaluation of the investment shows that the economic benefit is given, however due to the long payback time not attractive for current investment strategies in new applications. Optionally, this indication should be applied for component end of lifetime scenarios, with adequate machine tool longevity or as an input of future machine tool designs.

The research combines technical with economic approaches into one optimization strategy. Retrofit and refurbishment activities can be evaluated based on machine tool measurements, primarily addressed to the peripherals. In the case of the indication of potential field of actions, known economic evaluations can be applied in an effective way.

The central point is the mode of operation of each component and joint costs for retrofit and refurbishment.

This method is considered a promising assessment with two combined approaches, technical and economic, to achieve goals in sustainability within manufacturing. It relies on a


15 Handbuch Planung und Projektierung wärmetechnischer Gebäudesanierung, 1988, Bundesamt für Konjunkturfragen, Bern.

