Machine Tool Optimization Strategies -
Evaluation of Actual Machine Tool Usage and Modes

A. Gontarz 1, F. Hänni 1, L. Weiss 2, K. Wegener 1
1 Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology, Switzerland
2 inspire AG Zurich, Switzerland

Abstract
The research activities of today not only strive to cope with the legislative pressure given by the Directive of the European Parliament on Energy Using Products but also aim for economic advantages for the machine tool user by investigating and applying suitable procedures and methods that help to model, forecast, and reduce the overall energy and resource consumption. The common goal is to reduce the amount of resources consumed and increase machine tool efficiency with the help of selective methods and a minimum investment. An approach to identify the above mentioned advantages is given on the presented research work and paper. This paper introduces a methodology for detecting and defining reasonable investments for retrofit solutions and optimization strategies depending on the actual circumstances, an approach for the effective acquisition of the required data, and the strategy used to detect optimization potentials based on these findings.

Keywords:
Sustainable Manufacturing; Retrofit; Machine Tool evaluation; resource efficiency

1 INTRODUCTION
As the costs for resources for manufacturing on shop-floor level, e.g. energy, can be identified and directly assigned to their consumers, the further need is to determine potential fields of action for the energy efficiency improvement.

Today, machine tool manufacturers and their customers are beginning to adjust their behaviour towards environmentally benign manufacturing by having a clearer picture of the energy use of machine and production lines. Multiple measurement initiatives, e.g. Duflou [1] and own measurements [2], can provide a clear picture of a machine tool energy and resource consumption behaviour. Unfortunately, today, this ability is not very common in the industrial environment. The ability to decide consciously based on hard facts about design aspects that have influence on both the energy consumption and investment is an important aspect of competitiveness in the future and might also be mandatory due to EU legislation [3].

Without the knowledge of manufacturing and machine tool operational information, as well as the adequate interpretation of this data, a reasonable prediction of the energy consumed and corresponding design changes cannot be made. As machine tools are complex and individual and the energetic behaviour of their components is strongly dependent on the operation mode, energy prediction models are uncertain in many cases.

This knowledge gap 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 shop-floor level. As the machine tools lifetime and use phase is expected to last more than ten years [4], retrofit must be considered, not only for maintenance and service reasons but also for continuous improvement during this period.

2 STATE OF THE ART
To fulfil the above mentioned challenges and to provide an effective way to improve a production system, retrofit is seen as an effective technique for optimization. An internal study among Swiss machine tool manufacturers discloses an underestimated potential for retrofit solutions. Kirchner [5] ascertains that the machine tool design is not suitable to energy consumption criteria, mainly due to the peripheral design and the inter-peripheral adjustment. Weule [6] and Weyland [7] point out the ecologic and economic potential of the re-use of peripheral systems, which also affirms that the combination of change and the improvement of system components can only be made by retrofitting. Control suppliers such as Heidenhain, Siemens, and Bosch provide methods and a list of potential solutions for the resource efficiency improvement. The challenge remains the proper localization and selection of appropriate, economic, and ecologic solutions.

The focus within this research paper is the detection of potential for retrofitting particularly in respect of peripheral equipment whereas the process zone and its needs remains unquestioned. This focus is preferred since a broad measurement database shows that there is less potential for optimization for inner process related components.

Within the Life Cycle Assessment of machine tools, a gap in the ability to determine the potential field of action for a given machine tool setting and process by can be identified. The goal, 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. In the following, retrofit procedures are primarily understood as a modification or optimization of the peripheral equipment of the machine tool, including inner-peripheral adjustments, control, or the re-sizing of the components according to the given requirements.
3 METHODOLOGY

3.1 Retrofit indicator

The developed methodology is represented by three steps. It is based on two major aspects of a machine tool that are assumed to define the energy efficiency of a machine tool as follows:

- Energy consumption of the machine tool component: Components with high share of the energy consumption are assumed to also have 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.

These assumptions are combined in the following formula and represent an indicator for potential retrofit $I_R$:

$$ I_R = A_E \cdot A_O $$

(1)

Formula (1) with $A_E$ [], representing the energy 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, defines the retrofit indicator $I_R$. Herewith $A_O \approx 1$ represents a constant energetic behaviour, e.g. an open controlled-, and $A_O \approx 0.5$ represents an alternating, closed loop controlled mode. The calculation of $A_O$ is represented by Fig.7.

3.2 Methodological steps

Step 1 – Detailed machine tool measurement

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

- Definition of appropriate system boundaries.
- Definition of operation states and definition of shift regime for the given machine tool manufacturing environment, i.e. the share of time of each operation state within the observation period.
- Definition of a reference process for the operation state “machining”, that exploits the capabilities of the machine tool and defines a basis for optimization.
- Accounting of all relevant energy forms as in- and outputs to and from the system boundaries simultaneously.
- Selection of appropriate component clustering for the retrofit evaluation, e.g. functional oriented machine tool components that refer to machine or process cooling, tool and part handling, or waste handling.

A sequential component measurement can be applied as well, however the energetic behaviour of the components depends on environmental and infrastructural constraints, e.g. thermal state, a simultaneous measurement is recommended. For an example for a potential measurement system and appropriate consumer selection, it is further referred to Gontarz [8].

Step 2 – Calculation of retrofit indicator $I_R$

For each selected and investigated machine tool component, the retrofit indicator $I_R$ must be determined. According to formula (2), the energy share of each component $i$, $A_{E,i}$, is calculated as follows:

$$ A_{E,i} = \frac{E_i}{E_{System}} = \frac{\int P_i(t) \cdot dt}{\int P_{System}(t) \cdot dt} $$

(2)

$E_i$ [kWh]: Energy supplied to component $i$ during observation period.

$E_{System}$ [kWh]: Energy supplied to machine tool, accordingly to system border definition.

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

$P_{System}(t)$ [W]: Total effective power of machine tool, accordingly to system border definition.

$\Delta t = t_1 - t_0$ [s]: Observation period.

For the calculation of the second factor $A_O$, representing the operational mode of the component, the time at level counting procedure is used. It is taken from the fatigue strength analysis to analyse rotating loads, and the load characteristics, and to determine the life time of a part. Methods like rainflow or time at level counting [9] were investigated and reviewed for this application.

$$ A_{class} \rightarrow P_i(t) $$

Figure 1: Process chart for $A_O$ calculation.

An analysis of available counting methods revealed that time at level counting fulfills the analysis requirements to the full extent through a clear and easy-to-read statement. Due to high value levelling, the application of mathematical variance calculation is not sufficient for the mode of operation definition from the effective power plot. Fig. 1 shows the procedure by using a modified and extended time at level counting calculation.

Time at level counting is suitable for providing a mathematical verification of the operation mode of the consumer. The effective power levelling during the process duration is classified into equidistant classes of, for instance 0.1 kW. In each class, the duration of remaining on specific power level of each component can be determined. This represents a clear picture of the energetic behaviour of each component.

A component with a constant energetic behaviour requires energy on one specific level. Components with an open loop
controlled energetic behaviour are represented by more different energy levels. Resulting from this, components with several different energy levels represent variable components and can be classified with this applied mathematical approach. To estimate the indicator \( A_0 \) in formula (1), it is needed to add up the duration within the defined classes. This is represented graphically in Fig.3. This levelling can be approximated with a regression line. Finally, the gradient of the applied regression line represents the degree of the operational mode of each component (Fig.4).

The appropriate definition of the class width \( \Delta_{\text{class}} \) is needed for the signal interpretation, but is also dependent on several aspects, e.g. signal noise and signal quality and the resulting calculation period. Wide class ranges could lead to false interpretations of the effective power signal; tight class ranges increase the calculations time without any improvement in the information content.

A class width of \( \Delta_{\text{class}} = 0.005\cdot(\max(P_i(t)) - \min(P_i(t))) \) is selected and verified accordingly to the above mentioned requirements. The class definition and corresponding quantity are represented by:

- Positive-oriented effective power leveling:
  \[ n \in N \cap 1 \leq n \leq \frac{\max\{P_i(t)\}}{\Delta_{\text{class}}} + 1 \]  
  \[ n \in N \cap 1 \leq n \leq \frac{\max\{P_i(t)\}}{\Delta_{\text{class}}} + 1 \]  
  \[ n \in N \cap 1 \leq n \leq \frac{\max\{P_i(t)\}}{\Delta_{\text{class}}} + 1 \]  

- Negative-oriented effective power leveling:
  \[ p \in N \cap \min\{P_i(t)\} + 1 \leq p \leq 0 \]  
  \[ p \in N \cap \min\{P_i(t)\} + 1 \leq p \leq 0 \]  
  \[ p \in N \cap \min\{P_i(t)\} + 1 \leq p \leq 0 \]  

In the case of \( \min\{P_i(t)\} \geq 0 \), no classes are needed in the negative-oriented effective power leveling. Hereewith it is considered:

The applied class definition and the time at level counting is visualized in the following figures (Fig. 2 and Fig. 3).

Fig. 2 shows the measured effective power leveling, represented by the black dotted line, and the assigned classes, indicated by the black horizontal lines. The time at level counting, respectively the duration of the measured effective power values, are shown in the following Fig. 3. Beginning with the highest effective power level, in descending order, values of each class are summarized. To provide a comparison over all evaluated machine components, both axes must be normalized with the maximum effective power \( P_{\text{max}} \) and time \( t_1 \). This calculation is done for each component.

![Figure 2: Example of classifying an effective power-time measurement.](image)

![Figure 3: Summarized level durations on each effective power level and resulting data points](image)

The discrete normalized effective power values are organized equidistantly in the ordinate direction (Y-axis) with a constant width of \( \Delta_{\text{class}} \). The data points allocation in abscissa direction (X-axis) is dependent on the sum-level-duration levelling plot and, for this reason, is not equidistant.

The quantity of data points between the two axes as well: horizontal levelling is defined with few data points and the vertical levelling is defined by many data points, which leads to a parameter sensitivity of the regression line gradients depending on \( \Delta_{\text{class}} \). This effect increases the more classes are passed by the measurement signal.

To solve this problem, an algorithm was applied to sample the sum-level-duration levelling plot equidistant along the data points. Therefore the horizontal and vertical sequence plots are weighted equally in the calculation of the regression line.

At first, the total length of the sum-level-duration plot is calculated by connecting all discrete normed effective power values by lines. The sum of these intervals is \( L_{\text{tot}} \). Here from the length increment \( L_{\text{inc}} \) is calculated with formula (6):

\[
L_{\text{inc}} = \frac{L_{\text{tot}}}{\frac{P_{\text{max}} - P_{\text{min}}}{\Delta_{\text{class}}}} 
\]

\( L_{\text{tot}} \): Total length of sum-level-duration plot.

\( P_{\text{max}} \): Highest effective power among all consumers.

\( P_{\text{min}} \): Lowest effective power among all consumers.

\( L_{\text{inc}} \): Length increment.
To find the corresponding points for the evaluation plot, a linear interpolation between the discrete normed effective power values is performed.

Finally, the gradient of a regression line through the allocated points quantifies the dimension of the operational mode of each consumer. The weighting factor $A_{Oj}$ is calculated according to formula (7).

$$A_{Oj} = \frac{90° - \alpha_j}{90°} \quad (7)$$

$\alpha_j$ [$°$]: Gradient of the regression line.

Fig. 4 shows the resulting graph with its gradient. Each gradient of the corresponding consumers can be herewith analyzed. By having both specific values $A_{Ej}$ and $A_{Oj}$ of each component, the retrofit indicator can be calculated.

**Step 3 – Determination of retrofit activity**

The above shown procedure for the evaluation of a retrofit indicator can now be applied to specify concrete fields of action after the performed and assessed measurement.

Consumers with the highest retrofit indicator value must be considered and approved for potential retrofitting activities with priority. These activities depend on:

- use and impact on the process stability and quality
- technical and operating expense for retrofit
- economic aspects.

In consideration of the above mentioned points, only retrofit measures are assigned with $A_{Ej} \geq 5 \%$. The following measures can be considered, sorted by increasing complexity:

- turn off consumer, if applicable
- apply adjusted control or reduced duty
- replace consumer by a more efficient one
- replace complete subsystem while providing same function.

**4 VERIFICATION OF METHODOLOGICAL APPROACH**

**4.1 Example on conventional lathe**

The developed methodology was applied on different machine tools, including a conventional lathe and milling machine. 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.

The herewith presented methodological approach was applied on a horizontal turning center with a two axis tool positioning system, dry processing and compressed air process cooling. The following retrofit indication depends on:

- reference scenario
- machine tool infrastructure and design
- reference process.

**4.2 Reference Scenario and Process**

For the most important mode of operation, machining, the definition of a reference process is needed for representative measurements. As by now there is no standard available. In the ISO 14955 series, currently under work in ISO TC 39 / WG 12, the definition of test pieces or test procedures is planned. This is not published at the moment. Nevertheless those discussions on action for retrofit must be based on the real application.

Within this work a reference process is defined as a typical machine tool process that represents the target process of the designed machine tool. In the present example, a hard turning process of an automotive pinion is applied with the following process data:

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>100</td>
<td>s</td>
</tr>
<tr>
<td>Cutting rate</td>
<td>150</td>
<td>m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.15</td>
<td>mm/r</td>
</tr>
<tr>
<td>Cutting volume</td>
<td>3605</td>
<td>mm³</td>
</tr>
<tr>
<td>E consumption</td>
<td>0.156</td>
<td>kWh</td>
</tr>
</tbody>
</table>

**Table 1: Reference process**

Fig. 5 represents the effective power plot of this process. The process scenario defines a typical process and a default shift regime. In the following process scenario contains the workpiece handling by the operator, the use of the tailstock to hold the workpiece, the workpiece clamping with the chuck, and the process cycle itself.

**4.2 Reference Scenario and Process**

For the most important mode of operation, machining, the definition of a reference process is needed for representative measurements. As by now there is no standard available. In the ISO 14955 series, currently under work in ISO TC 39 / WG 12, the definition of test pieces or test procedures is planned. This is not published at the moment. Nevertheless those discussions on action for retrofit must be based on the real application.

Within this work a reference process is defined as a typical machine tool process that represents the target process of the designed machine tool. In the present example, a hard turning process of an automotive pinion is applied with the following process data:

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>100</td>
<td>s</td>
</tr>
<tr>
<td>Cutting rate</td>
<td>150</td>
<td>m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.15</td>
<td>mm/r</td>
</tr>
<tr>
<td>Cutting volume</td>
<td>3605</td>
<td>mm³</td>
</tr>
<tr>
<td>E consumption</td>
<td>0.156</td>
<td>kWh</td>
</tr>
</tbody>
</table>

**Table 1: Reference process**

**4.2 Reference Scenario and Process**

For the most important mode of operation, machining, the definition of a reference process is needed for representative measurements. As by now there is no standard available. In the ISO 14955 series, currently under work in ISO TC 39 / WG 12, the definition of test pieces or test procedures is planned. This is not published at the moment. Nevertheless those discussions on action for retrofit must be based on the real application.

Within this work a reference process is defined as a typical machine tool process that represents the target process of the designed machine tool. In the present example, a hard turning process of an automotive pinion is applied with the following process data:

<table>
<thead>
<tr>
<th>Data</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>100</td>
<td>s</td>
</tr>
<tr>
<td>Cutting rate</td>
<td>150</td>
<td>m/min</td>
</tr>
<tr>
<td>Feed rate</td>
<td>0.15</td>
<td>mm/r</td>
</tr>
<tr>
<td>Cutting volume</td>
<td>3605</td>
<td>mm³</td>
</tr>
<tr>
<td>E consumption</td>
<td>0.156</td>
<td>kWh</td>
</tr>
</tbody>
</table>

**Table 1: Reference process**

Fig. 5 represents the effective power plot of this process. The process scenario defines a typical process and a default shift regime. In the following process scenario contains the workpiece handling by the operator, the use of the tailstock to hold the workpiece, the workpiece clamping with the chuck, and the process cycle itself.
In the following an example calculation for the retrofit indicator \( I_R \) is shown for a specific consumer.

### 4.3 Calculation of retrofit indicator \( I_R \)

Due to the amount of calculations, for each relevant consumer, one calculation as an example is selected. The energy required for the compressed air system is suited due to a clear statement within this methodology and it also represents one of the main potential retrofit activity options. The measurement bases upon the above mentioned reference process and scenario.

Fig. 6 shows the isolated effective power measurement of the compressed air system. A detailed calculation of the required compressed air energy is referred to Gontarz [2].

![Figure 6: Effective power of compressed air during reference process.](image)

Fig. 6 also shows the classification with defined class width. The effective power characteristic shows two major power levels, during and off the process cycle, and compared to the total effective power use a high share of effective power. With a maximum effective power over 3 kW and a resulting required energy use of 0.036 kWh during the reference process \( A_{E,Air} \) results according to formula (2) to:

\[
A_{E,Air} = \frac{E_i}{E_{System}} = \frac{0.0365}{0.1560} = 0.234
\]

In addition, the calculation of the mode of operation factor \( A_0 \) is shown exemplary in Fig. 6, 7 and 8. By adding up all measurement point durations and scaling, Fig. 7 approves the assumption of a two level periodic energetic behaviour of the compressed air system.

In the next step, the regression line can be drawn according to the given measurement points and formula (3) in the scaled plot Fig. 8. This formula provides multiple equidistant points along the path. This plot can be compared among each component to determine its actual mode of operation.

![Figure 8: Scaled plot with regression line.](image)

Finally, the angle of the regression line can be determined to calculate the \( A_{A0, Air} \) factor with formula (4). In the present case, the angle \( \alpha_i \) is \( 26.4^\circ \) and results in \( A_{A0, Air} = 0.707 \). Table 2 shows the results for the detected possible retrofit activity points.

<table>
<thead>
<tr>
<th>Measurement M12, lathe, pinion</th>
<th>( A_{E,i} )</th>
<th>( A_{A0,i} )</th>
<th>( \psi_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air compressor</td>
<td>0.234</td>
<td>0.71</td>
<td>0.166</td>
</tr>
<tr>
<td>Cooling fan spindle</td>
<td>0.166</td>
<td>0.993</td>
<td>0.166</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>0.119</td>
<td>0.982</td>
<td>0.117</td>
</tr>
<tr>
<td>CNC Total</td>
<td>0.182</td>
<td>0.612</td>
<td>0.111</td>
</tr>
<tr>
<td>Spindle cooling pump</td>
<td>0.109</td>
<td>0.993</td>
<td>0.108</td>
</tr>
<tr>
<td>Sealing air</td>
<td>0.058</td>
<td>0.993</td>
<td>0.058</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

### 4.4 Definition of retrofit activity

The performed assessment with the retrofit indication pointed out fields of action on the given machine tool and in the given process. It 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 influence the machining process, the investigations were 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. Fig. 9 shows the effective power of the hydraulic system during the applied reference process. The hydraulic pump constantly requires 680 W effective power to maintain the system pressure. Apart of maintaining a constant pressure it is actually used less than 10s during the total reference process.
According to the given retrofit definition and the possible retrofit activities (chapter 3) the hydraulic system can be either controlled or replaced by a more efficient and appropriately dimensioned one. It could be replaced by a hydraulic pump combined with a reservoir system.

This retrofit solution is suitable for the assessed reference scenario. It might be not suitable for other applications.

![Figure 9: Effective power of hydraulic system with open- and lock chuck for workpiece clamping.](image)

Further research with the focus on the appropriate selection of retrofit action as several dependencies, e.g. economic, service and maintenance, as well as flexibility issues must be considered.

5 CONCLUSION

According to the given reference process and scenario, as well as the machine tool system design, the retrofit indication determined and rated potential retrofit fields of action. It approves the assumptions of potential improvement fields by a mathematical statement that can be furthermore evaluated under the consideration of different scenarios or machine tool system designs. This method is considered as a promising assessment to deal with energy measurement data; however, it requires a detailed energy measurement on the component level and needs to be approved by a retrofit verification measurement.

6 SUMMARY

The research evaluates how retrofit activities under the aspect to reduce energy consumption could be found based on machine tool measurements. It is primarily addressed to the auxiliary but could also be extended to process related components. Measurements on the machine tool level are necessary only if instrumental information cannot be withdrawn from the control. It is therefore necessary to interpret the measurements accurately. For appropriate data information, methodologies and calculations from other research fields can be adopted.

Starting with the overall machine tool measurement, this methodology evaluates the energetic behaviour and share of each machine tool component. The central point is represented by the time at level counting. This calculation detects the mode of operation of each component.

This methodology likewise enables the machine tool builder in the future machine tool design and machine tool users to improve machines in the field.

Further research must be done to determine at which spots and degree retrofit could be applied, principally considering economic requirements, e.g. return on investment. Appropriate retrofit decisions are also needed in service and maintenance applications.

As the presented methodology relies on a clear input, the effective power measurement and corresponding components, it is considered a quick and powerful assessment tool and serves furthermore as a base for further research.

7 ACKNOWLEDGMENTS

We gratefully appreciate the funding of CTI Switzerland and extend our sincere thanks to MAG Switzerland for cooperation.

8 REFERENCES


