3.6 Machine Tool Optimization Strategies:
Evaluation of Actual Machine Tool Usage and Modes

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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. Dufliou [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 $\textit{l}_R$:

$$ I_R = A_E \cdot A_O $$  \hspace{1cm} (3.6.1)

Formula (201) 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 $A_E = 1$ represents a constant energetic behaviour, e.g. an open controlled-, and $A_E = 0.5$ represents an alternating, closed loop controlled mode.

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 bases 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 (3.6.2), the energy share of each component $i$, $A_E i$ is calculated as follows:

$$ A_{E,i} = \frac{E_i}{E_{\text{System}}} = \frac{\int_0^{t_1} P_i(t) \cdot dt}{\int_0^{t_1} P_{\text{System}}(t) \cdot dt} $$  \hspace{1cm} (3.6.2)

$E_i$ [kWh]: Energy supplied to component $i$ during observation period.
$E_{\text{System}}$ [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.
$P_{\text{System}}(t)$ [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 rain flow or time at level counting [9] were investigated and reviewed for this application.

$$ \Delta \text{class} \quad P_i(t) $$

Fig. 3.6.1 Process chart for $A_O$ calculation

An analysis of available counting methods revealed that time at level counting fulfils 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. Figure 3.6.1 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.