Conference Paper

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Publication Date: 2012

Permanent Link: https://doi.org/10.3929/ethz-a-007577766

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Energetic machine tool modeling approach for energy consumption prediction

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Abstract
The knowledge of the energy flow within machine tools and of the manufacturing environment is crucial for further substantial improvements in development of energy efficient machines and energetic optimization. Measurements have revealed that in addition to machining processes, auxiliary equipment could have a major impact on the power consumption of the machine tool system.

Various statistical, physical and hybrid modeling approaches on different system levels from machining to manufacturing processes exist, whereas a modular approach, which is based on only a few essential parameters for the prediction of energy and thermal behavior with the inclusion of auxiliaries, does not exist. In conjunction with a user survey, this paper introduces a new physical modeling approach to predict the energy consumption and thermal impacts during various modes of the machine tool and its components.

The integrated approach, which is based on an established modeling framework, enables machine tool developers to optimize and select components in order to increase energy efficiency in manufacturing. This approach is validated on a turning machine.

Keywords:

1 INTRODUCTION
Energy efficiency and resource saving constitute a considerable topic in society, politics and industry. As a major energy consumer and CO2 emitter [1] the industrial sector must be aware of consumption and must adopt the minimization of energy waste.

References to energy waste pertain to the energy consumption of machine tool components which are not needed in certain activities, e.g. during standby, or the over-dimensioning of components. Waste heat has to be considered also as it is not only a problem of energy costs but requests certain actions as well: heat release can affect precision and the thermal stability of machines and productions. Consequently, energy waste is not only a financial problem but the activator for an entire chain of processes and influences.

Like other active products, machine tools have a dominating energy demand during the use phase [2]. Therefore, a substantial contribution to global efficient energy use can be achieved by optimizing the use phase of a machine tool. A predicament is given; while in the early development phase, the product and its properties, performance and behavior are defined, information by fixing design parameters, the consequences for the use phase are not really known, as it was also complained in [3]. Moreover, prototypes for measurements and validation might not be available during this phase.

A machine tool in general an assembly of components such as drives, pumps, fans and others. The energetic behavior of the machine tool is thereby characterized by the connected components, their energetic behavior, and the interaction between them and their subsystems.

To reveal information about the energetic behavior of the final machine tool during the early development phase, a method is requested which can estimate the energy flow between the components based on the little information available in this phase.

The research therefore introduces a machine tool energy model (EMod) that represents the significant physical effects on a machine tool system. The requirements of such an energetic model are primarily a small number of input parameters and the flexibility for the model implementation on various machine tool systems.

The small number of parameters results from the limited information available in the early development phase, where the flexibility is required to overcome the large number of different machine tool applications, their usage, types and configurations available.

2 STATE OF THE ART
In literature various types of machine tool models can be derived. As a detailed description of effects and system dynamics, a model can be described with different approaches and classified in physical, statistical, and black-box models. Furthermore, the model type, size and system boundary can vary.

Process models for energetic models represent a focused system boundary and describe relevant forces and velocities under certain process conditions. For instance, Kienzle et al. [4] have described models for forces in metal cutting. In relation to cutting parameters the required mechanical energy to provide those forces can be calculated. Draganescu et al. [5] propose a statistical approach where the transformation efficiency of electrical to mechanical power is set in
dependence of the process parameters. An empirical approach is shown by Li and Kara [6] which comprises a wider system boundary by including auxiliary devices. Following the same approach, Kardonow [7] approved the energetic importance of auxiliaries, which is consistent with the statement on the energetic behavior of machine tools by Dahmus and Gutowski [8].

Physical models of energetic consumers which were assured by measurements for the identification of system parameters, e.g., motors, pumps and valves, was applied by Eisele et al. [9]. This approach is seen as a tool for the optimization of the overall efficiency on the machine tool by manipulating the component parameters. As the interconnection of different consumers of a machine tool reflects the total energetic behavior, a modular machine tool model is required. Verl et al. [10] describe generic components of a machine tool with defined in- and outputs. This approach guarantees the interchangeability of components and can be used for further optimization activities.

An approach of the combination of the above mentioned statistical and physical models is done by Avram [11]. In his method Avram uses physical models, which are based on a large set of parameters, and black-box models. Another energy efficiency optimization model with wide system boundaries is represented by the Total Energy Efficiency Management (TEEM) by Hornberger et al. [12]. It focuses on overall factory optimization with individual and interconnected approaches. As this approach is situated on the manufacturing level, it neglects the interdependency of system components.

In summary, different approaches can be distinguished which consist of a variety of focuses on optimization. For optimization procedures on the whole machine tool system, the interconnection and interoperability of components as well as the physical foundation are important. This requirement is currently not sufficiently answered in literature. Furthermore, a large majority of the reviewed approaches bases on existing machine tools and manufacturing systems, the development of new machine tool systems is hardly supported.

3 METHODOLOGY

3.1 Requirements and Architecture

Resulting from the literature review and related work, there is an absence of an energy machine tool model that is flexible, with interchangeable components and a parameter setting with decent parameterization effort; this is requested by industry in order to enhance new machine tools during early development stages. In an approach from coarse to fine, a survey among Swiss SMEs [13] revealed some general and important requirements for capabilities of machine tool energy models:

- Comparison of different machine tools in various operating modes.
- Identification of energy-inefficient components and/or indication of over-dimensioning.
- Comparison of different machine tool components and their energetic behavior.

Furthermore, an energy model requires adequate precision, which is set accordingly to further validation and made assumptions to ± 20%. As an extrapolation and prediction tool this error range appears to be sufficient as this contains the measurement, implementation and logical errors. In conjunction with these requirements, an open architecture for further individual implementation without a costly licensing procedure can be realized by an open JAVA application.

Figure 1 introduces the basic structure and procedure of the energy model framework (EMod) [14]. It contains a configuration procedure based on given inputs as a component database which is linked to a physical model library. The actual simulation leads to an analysis procedure and further outputs in accordance with the above mentioned requirement of the industry.

In addition to these general requirements, some assumptions, limitations and implementation requirements have to be considered in the development of the target machine tool energy model.

In order to guarantee the modularity and interchangeability within the machine tool subsystems, it has been decided that the model must be designed and evaluated upstream the energy flow; that means the energy flow is depended on the next higher aggregation level and does not influence subsystems downstream the energy flow. Thus, in accordance with Guzzella et al. [15], a quasi-static simulation (QSS), also known as effect-cause simulation is applied. Through the consideration of component interconnection, low application complexity and the indication of essential energetic behaviors, transient activities, e.g., spindle start-up, are neglected in this model approach. This simplification is considered true for low dynamic machine tool activities.

The requested energy demand on the main drives is initiated by defined and requested process energy in the process zone, e.g., chip cutting energy; additionally, it defines further activities of auxiliary systems and subsystems.

According to the main drives, the power consumption of auxiliary devices is calculated and is dependent on the component state. In a QSS, only components which upstream the energy flow are influenced by a change at a certain point of the model. Furthermore, by using QSS the simulation times can be reduced in comparison to a dynamic simulation within a complex environment; this is due to the reduced number of differential equations. The direction of evaluation within this model is therefore given with:

\[ P_{out} = f(P_{in}) \iff P_{in} = f^{-1}(P_{out}) \]  

If a subsystem is represented by the function f, which is invertible, the relation between the input power \( P_{in} \) and the required output power \( P_{out} \) is given in formula (1).
Interoperability can be achieved by defined generic components. For instance, a generic component can be represented by a motor with pre-defined inputs, e.g. rotational speed and torque, and outputs, e.g. consumed power and heat loss. Subsystems of the same generic type therefore have the same interfaces and can be replaced by another generic component of the same type. Figure 2 shows an example of the total interrelation of components with different generic types and their in- and outputs.

In Figure 2 the system boundary is represented by dashed lines (-) whereas physical signals are represent by solid lines (—). The initial starting point for the effective power calculation is located at the cutting process.

### 3.2 Development of generic components

The development of generic components is represented in the configuration, the component database, and the physical modeling step as indicated in Figure 1.

The term “generic” relates to a characterization of the components by their function, regardless of the component type. For instance, the generic component electrical drive is represented by various types of electrical drives, such as synchronous and asynchronous motors. The function remains the same for all drives: Transforming electrical power into mechanical power.

In the following subsections, some major elements of the machine tool energy model will be introduced and described in more detail.

#### Cutting process

In order to validate the modeling results, the machine tool energy model was applied on a turning machine Schaublin 42L. As described in the previous chapter, the basis for the energetic evaluation of all machine tool components is given by the process forces and required energy. In this context the Kienzle model [4] is used.

For the cutting process the following turning process parameters are considered: Rotational speed of the main spindle \( \omega_c \), the translational speeds of the z-axis \( v_z \) and x-axis \( v_x \), and the cutting depth \( a_p \). Moreover, parameters on the work piece material, cutting tool and angle of setting \( \alpha \) between the work piece and cutting tool are needed. Relevant parameters can be found as statistical data in literature. As these parameters are strongly dependent on the individual work piece and tool - relationship, force measurements were performed to reveal the exact Kienzle - parameters for the given test case scenario.

According to this approach the cutting force \( F_c \) (Formula (2)), feed force \( F_f \) and passive force \( F_p \) can be calculated whereas \( F_c \) is relevant for the torque calculation of the spindle.

\[
F_c = b \cdot h \left( \frac{2 \cdot \xi \cdot v_z}{\omega_c} \cdot \sin \alpha \right) \cdot k_{c1.1} \cdot 1^z \cdot k_{c1.1}
\]  

(2)

When applying the equation to the model, the relation between rotational speed \( \omega_c \), feed rate \( v_f \) and chip dimension have to be made, while constant chip dimension with constant diameter and no z-movements are assumed. With the applied assumptions and further geometrical simplification, the resulting cutting force \( F_c \) is represented by Formula (3):

\[
F_c = \frac{a_p}{\sin \alpha} \left( \frac{2 \cdot \xi \cdot v_z}{\omega_c} \cdot \sin \alpha \right) \cdot k_{c1.1} \cdot 1^z \cdot k_{c1.1}
\]  

(3)

- \( b \) [mm]: Chip height
- \( v_x \) [mm/s]: Cutting speed
- \( a_p \) [mm]: Cutting depth
- \( \omega_c \) [rad/s]: Rotational speed
- \( \alpha \) [deg]: Angle (static)
- \( 1^z \): Corrective factor
- \( k_{c1.1} \) [N/mm²]: Unit specific cutting force coefficient

For simulation and consumption evaluation of the axis the feed force \( F_f \) is further used for the linear axis power consumption calculation.

#### Motor

Various types of electrical drives exist, e.g. synchronous or asynchronous motors. For the asynchronous motor with given rotational speed \( \omega(t) \) and torque \( T(t) \), the mechanical power is calculated according to:
Compressed air has various applications in machine tools, such as cooling, material removal, part clamping and sealing air. Previous measurements have shown [16] that the energy demand on a machine tool in the form of compressed air can be significant. The compressed air supply and production is assumed to follow an adiabatic transformation and includes an isentropic compression from ambient conditions to nominal volume by a compressor, followed by an isochoric temperature drop. At the outlet of the machine tool, compressed air undergoes an isentropic expansion to ambient pressure and an isobaric expansion to ambient temperature.

Within an adiabatic process the change in the internal energy is equal to the compression work on the gas. With a given temperature \(T\) to represent the temperature after the compression, the change in the inner energy, which is equal to the work done, is:

\[
P_{\text{cair}}(t) = c_{p, \text{air}} \cdot (T_2 - T_\text{amb}) \cdot \dot{m}_{\text{cair}}(t) \quad \text{and} \quad \dot{q} = \dot{m}_{\text{cair}} \cdot (T_2 - T_\text{amb})
\]

(7)

\[
p = \gamma \cdot R \cdot \dot{V}
\]

(8)

\[P_{\text{cair}} \text{[kW]}: \text{compression work done} \quad \dot{q} \text{[K]}: \text{temperature after comp.} \]

\[c_{p, \text{air}} \text{[J/KgK]}: \text{internal heat capacity} \quad \dot{m}_{\text{cair}} \text{[Kg/s]}: \text{air mass flow} \]

\[\eta \text{[Pa]}: \text{ambient temperature} \quad \dot{m} \text{[kg]}: \text{gas mass} \]

\[V \text{[m}^3\text{]}: \text{gas volume} \quad R \text{[J/kg K]}: \text{specific gas constant} \]

\[\rho_1 \text{[kg/m}^3\text{]}: \text{air density} \]

If \(\eta(T, \omega)\) is known, then the effective power demand \(P_{\text{tot}}\) can be calculated by using the mechanical power demand \(P_{\text{mech}}\). In most cases the motor efficiency is known from an efficiency map given as catalogue data. The resulting efficiency for a given \(\eta(T, \omega)\) can be approximated by using linear interpolations within the efficiency map. The same approach is given for servomotors, which are considered as motors connected to an amplifier, which was modeled also within this framework.

**Pump**

A component of the type pump moves an incompressible fluid. A pump produces a pressure difference which leads to a mass flow. For a given mass flow \(\dot{m}(t)\) demand and a state of operation, the requested power is calculated. It is assumed that a pump has only one power level when it is on. Given further the characteristic map \(f\) of the pump, such that \(\Delta p(t) = f(\dot{m}(t))\), the power demand \(P_{\text{tot}}\) and heat loss \(Q_{\text{loss}}\) are described by:

\[
P_{\text{tot}} = P_{\text{amp}} \cdot h(\dot{m}(t)) \quad \text{and} \quad Q_{\text{loss}} = P_{\text{tot}} - \dot{m}(t) \cdot f(\dot{m}(t))
\]

(6)

where \(h(\cdot)\) indicates the unit step function. Similar as for the motor efficiency map, linear interpolation is used, in order to express the pump map \(f\) in dependence of a set of known operational points \((\dot{m}, \Delta p)\). The thermal loss, calculated in equation (5), could be used to estimate the thermal impact of the component, based on available catalog values.

**Compressed air**

Compressed air has various applications in machine tools, such as cooling, material removal, part clamping and sealing air. Previous measurements have shown [16] that the energy demand on a machine tool in the form of compressed air can be significant. The compressed air supply and production is assumed to follow an adiabatic transformation and includes an isentropic compression from ambient conditions to nominal volume by a compressor, followed by an isochoric temperature drop. At the outlet of the machine tool, compressed air undergoes an isentropic expansion to ambient pressure and an isobaric expansion to ambient temperature.

Within an adiabatic process the change in the internal energy is equal to the compression work on the gas. With a given temperature \(T\) to represent the temperature after the compression, the change in the inner energy, which is equal to the work done, is:

\[
P_{\text{cair}}(t) = c_{p, \text{air}} \cdot (T_2 - T_\text{amb}) \cdot \dot{m}_{\text{cair}}(t)
\]

(7)

\[
p = \gamma \cdot R \cdot \dot{V}
\]

(8)

\[P_{\text{cair}} \text{[kW]}: \text{compression work done} \quad \dot{q} \text{[K]}: \text{temperature after comp.} \]

\[c_{p, \text{air}} \text{[J/KgK]}: \text{internal heat capacity} \quad \dot{m}_{\text{cair}} \text{[Kg/s]}: \text{air mass flow} \]

\[\eta \text{[Pa]}: \text{ambient temperature} \quad \dot{m} \text{[kg]}: \text{gas mass} \]

\[V \text{[m}^3\text{]}: \text{gas volume} \quad R \text{[J/kg K]}: \text{specific gas constant} \]

\[\rho_1 \text{[kg/m}^3\text{]}: \text{air density} \]

Further by inserting the values \(c_{p, \text{air}} = 1013 \text{J/kgK}, \theta_\text{amb} = 273\text{K},\) specific heat ratio \(\gamma=1.4,\) pressure ratio \(p_1/p_\text{amb} = 8\) for typical industry pressurized air nets and \(p_1 = 1.2 \text{ kg/m}^3\), the equation can be simplified to:

\[
P_{\text{cair}}(t) = C_{\text{air}} \cdot \dot{V}_{\text{a,air}}(t)
\]

(9)

\[C_{\text{air}} \text{ represents the requested power to realize a desired supply and is calculated to } C_{\text{air}} = 7.2 \text{ kW/m}^3\text{min. Within the generic type “compressed air” the input values are the flow rate } \dot{V}_{\text{a,air}}, \text{ambient pressure } p_\text{amb} \text{ and ambient temperature } \theta_\text{amb}. \text{ Those parameters are needed for the modeling to result in electric power demand.} \]

**Constant consumers**

Another important group of consumers is represented by constant consumers. As mentioned in the state of the art [8] these consumers mostly represent auxiliary devices that can have a significant share of the total energy demand.

Dependent on the machine tool operation mode, e.g. on, standby, process or off mode, some consumers disclose constant energetic behavior, such as in process with the nominal power \(P_{\text{nom}} = P_{\text{tot}}\). For instance, consumers with constant power consumption are fans or pumps with defined component states, e.g. on, transient and off. In the machine tool energy model different machine states \(S_{\text{cmp}}(t)\) must be mapped on defined component states \(\sigma(S_{\text{cmp}})\).

Such states once again cause defined power consumption outputs that can be measured or assumed \((P_{\text{off}})\).

Constant consumers can therefore be calculated according to the following procedure:

\[
S_{\text{cmp}}(t) = \sigma(S_{\text{mch}}(t)) \quad \text{and} \quad P_{\text{tot}}(t) = \sum(S_{\text{cmp}}(t))
\]

(11)
4 MODEL VALIDATION AND ANALYSIS

4.1 Identification of operational states

For validation the data produced by the machine tool energy model has to be verified with measurements. In addition, an analysis of the error sources is done in order to identify the reliability and practicability of the applied procedure. To validate the machine tool energy model, a standard turning process on a lathe type Schaublin 42L was performed.

The validation can be separated into different validation purposes. Initially, the basic modeling framework should be validated to detect errors in the configuration (Figure 1). This requires the identification of defined machine modes that can be mapped on operational states in the machine tool energy model. These modes are for instance defined as off, standby, ready and process and reflect the mentioned machine states \( S_{\text{mode}}(t) \) in the model. It must be assured that, depending on each operational state, the appropriate consumer behavior is defined, e.g. in off mode: compressed air is used as sealing air despite the fact that all main drives are off. This was validated by power measurements on the lathe.

In a second step the direct measurements on the lathe are compared to validate the parameterization and physical output of the modeled consumers. Two different measurements were performed in order to validate the simulated data. The effective power consumption and the compressed air flow were measured according to [17]. Secondly, the cutting force was measured using a dynamometer from Kistler AG [18].

The following cutting parameters for turning were chosen:

Table 1 Cutting parameters for turning process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material - 51CrV4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting speed ( v_c )</td>
<td>m/s</td>
<td>200-350</td>
</tr>
<tr>
<td>Feed rate ( f )</td>
<td>mm/rev</td>
<td>0.15-0.45</td>
</tr>
<tr>
<td>Cutting depth ( a_p )</td>
<td>mm</td>
<td>0.3-5.0</td>
</tr>
</tbody>
</table>

The selection of appropriate settings and the combination of parameters and material are based on a chosen reference process. The evaluation of the test series is done by a Design of Experiments methodology according to the procedure of Kleppmann [19].

Revealed by the technical description of the measurement equipment, the following uncertainties are expected on the measurement side:

Table 2 Expected errors for the measurement system.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Unit</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power sensor</td>
<td>W</td>
<td>&lt;±4.5%</td>
</tr>
<tr>
<td>Compressed air</td>
<td>Nm³/min</td>
<td>±3.5%</td>
</tr>
<tr>
<td>Force</td>
<td>N</td>
<td>&lt;±0.3%</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
<td>±1.0K</td>
</tr>
</tbody>
</table>

Figure 3 represents the calculated force measurement gained from the Kienzle model. The distribution represents a statistical ground and shows a relative error of the cutting force \( F_c \) of 8.3% compared to the force measurement. This distribution concludes that in 90% of all cases the calculated force has a deviation from the measured force of less than ±15%.

In the applied case of measured Kienzle-parameters on the lathe and obverse from values listed in literature, the model fulfills the requirements of accuracy. Due to the QSS approach, the proper calculation in the cutting force has a dominant influence on all remaining consumers.

Another deviation between the measured effective power and modeled consumer data arises from missing or unconsidered components, e.g. constant consumers that are omitted due to complexity reasons or poor information on the target system. The deviation leads to a relative error towards the main power supply prediction. Furthermore, as stated before, the energetic consumer behavior is dependent on the machine mode and running tasks. This dependency and the fact that consumption values are significantly higher between different machine tool modes have a resulting effect on the simulated data.

Summarizing the error calculation results compared to the power measurements, the error over the sum of all components is in the range of -1.5% during off mode, +15% during standby and ready mode and -1.5% in process mode compared to the sum of components’ power demand. By comparing with the total energy demand measured, the deviation is slightly higher (Figure 4).


5 RESULTS

Under the consideration of all above mentioned simplifications and required parameterization, a reference process can be simulated and shown exemplarily in Figure 5 as a P-t-diagram in the analysis section of the framework.

As the revealed data in the analysis is based on the effective power of all modeled components $P_i(t)$, multiple analysis and optimization activities, e.g. retrofit indication [20], functional-oriented evaluation [16] and others can be performed.

6 CONCLUSION

According to the comparison of the simulated data and measurements (Figure 5), as well as the discussed limitations, the given approach represents an accurate model to simulate complex mechatronic systems. This approach closes the gap between process focused and manufacturing simulation on one side and optimization activities on the other side. Moreover, it fulfills the given requirements and reflects the experience from machine tool measurements with the multichannel measurement system and common knowledge on machine tool energetic behavior [10].

Possible applications for this model are manifold. As intended, this approach is seen as an optimization tool for the development phase to detect over-dimensioning, losses and waste of energy in any kind before a machine tool is built. In addition to the approved accuracy, a potential application for this energy model is seen in monitoring systems by reducing sensor costs through approved models.

The validation of the model showed that the desired precision is only given under certain pre-defined circumstances, e.g. defined cutting processes, non-transient operations and pre-defined Kienzle parameters. Three main aspects are identified for having the biggest impact on the accuracy on the machine tool energy model.

- Missing or neglected constant consumers.
- The usage and identification of parameters, which affects all modeled consumers and are given through different evaluation sources, e.g. technical reports, measurements or assumptions.
- Simplification of the modeled physics. This affects mainly the modeled drives.

7 SUMMARY

The research evaluates a simulation approach for complex mechatronic systems to fulfill the need of future development of energy efficient machine tools.

Compared to other machine tool energy simulations, this approach focuses on the entire machine tool and its auxiliaries and introduces a generic component to enable the requested flexibility and modularity of this model. The simulation results underscore the energetic machine tool behavior in-line with the current research. The approach shows further the dependency of the results on available parameters, especially for the electro-mechanical part of the simulation. For a given lathe as reference machine, the model fulfills the required accuracy of ±20% in comparison to measured data.

A thermal model was not discussed within this paper but has to be considered due to its importance for thermal stability, quality and energy efficiency. Transient operations and drive accelerations were also neglected in this model. As this simplification is appropriate for the given test case, it might not be suitable for other cases.

A reference process definition and the knowledge of the actual machine tool utilization, e.g. defined standby and process times, are essential for reliable energy consumption predictions. A defined interface through xml files was therefore created. Additionally, a defined CAD/CAM-interface based on current standards, e.g. STEP NC, could be implemented for better application in industrial development.

As most of the requirements of the industry are covered, the presented machine tool energy model (EMod) is considered as a powerful tool for future optimization activities.

8 ACKNOWLEDGMENTS

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

9 REFERENCES


