ENERGY CONSUMPTION FORECASTING AND OPTIMISATION FOR TOOL MACHINES

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Soaring energy prices, signs of a human-made climate change and legislative pressure have brought the energy consumption of machines to the attention of machine tool builders and their customers. To enable manufacturers and operators of machines to include energy consumption into their considerations in an objective way, we introduce an efficient method to model the energy consumption behaviour of machines. Based on that, we present methods to forecast the actual power drain profile and to optimise machines for minimal energy consumption under any given application scenario

Keywords
Energy Efficiency, Virtual Prototyping, Machine Optimisation

1. Motivation

For decades, economies worldwide and most of all in Europe have been able to grow fast based on the almost unlimited availability of cheap energy and resources. First signs of the dependency on energy for prosperity have become apparent in the 1970s, with a number of economic setbacks resulting from energy shortages. In that decade, the acclaimed book 'The Limits to Growth' [Meadows 1972] highlighted the global consequences of limited resources for the first time. Since then, many new and large economies have entered the competition for resources with force, while new sources of energy have not been made available to the same extent. As a result, the energy prices have experienced a sharp increase and brought the cost for energy onto the agenda. Moreover, as most means to produce energy result in the emission of carbon dioxide to the atmosphere, human induced climate change is directly linked to the energy consumption worldwide and is expected to lead to additional cost in the future.

In addition to raising the consciousness of people worldwide, this has led to legislative pressure. A recent Directive of the European Parliament on Energy using Products [Directive 2005/32/EC] aims to establish a framework for the setting of ecodesign requirements for energy-using products. The final report [Working Plan of the EcoDesign Directive 2008] of a study group initiated by the European Commission cites tool machines as the top three priority for inclusion into the product categories to be regulated in this framework. Although the results of this study have been at the heart of some debate [Welcker 2008], it is highly probable that tool machines will be subjected to energy efficiency regulation and classification in the years to come.

Motivated by the mentioned financial and legislative pressure, enterprises that buy and operate tool machines are currently investigating methods to limit the life cycle cost of their production lines. The automotive industry will require energy consumption data to be included into bids in the upcoming years. Tool machine manufacturers will therefore have to be able to provide accurate data on the energy their products require to manufacture a product. Unfortunately, today neither the tool machine manufacturers nor their customers have a clear picture of the energy use of machines and production lines.

The ability to make informed decisions about design aspects that have an influence on both the energy consumption and the investment will be an important aspect of competitiveness in the future. While some measurements have been made, what has been missing is a practical method to predict the actual energy consumption. This paper therefore introduces a lean modelling technique that helps to overcome these limitations.

2. Elements of Efficiency

Before methods for energy consumption modelling and efficiency optimisation can be introduced, we have to take a closer look at what efficiency is and what factors contribute to the overall efficiency of manufacturing.

In theory, the efficiency of a machine is the ratio between the absolute minimum of the energy that is required theoretically for a task, $E_{min,abs}$ and the actual energy turnover of a real machine, E_{real}:

$$\eta = \frac{E_{\min,abs}}{E_{real}} \tag{1}$$

Unfortunately the theoretical minimum is often unknown for manufacturing applications. In a more informal way, efficiency can be seen as the result achieved compared to the effort required for that:

$$efficiency = \frac{benefit}{total\ effort} \tag{2}$$

Of course, this equation cannot be evaluated in this general form. In manufacturing, though, both benefit and effort can often be quantified monetarily, i.e. the benefit may be the earnings and the effort may be the total turnover attributed to a manufactured part. In the same way, the value of a product can be related to the energy required for its production. Obviously, the attainable value of this quantity is determined during product design, applying a trade-off between product efficiency and attainable production efficiency. While it is difficult to accurately predict, for a given design, production efficiency can be seen as a combination of a number of individual degrees of efficiency.

Typically, the first step in manufacturing a product consists of laying out the process chain leading from raw materials to the finished product. The form and characteristics of raw materials are often included in this step in the form of key figures [Abele 2003]. In addition to that, waste and recycling cost are taken into account to ensure resource efficiency. The goal is to find the combination of steps with the lowest total effort for a given product. Often, no explicit degree of efficiency can be given, as the theoretical minimum effort is not known, and thus the comparison is made based on absolute values, e.g. the total energy turnover:

$$E_{\Pr od} = E_{material} + \sum_i E_{step,i} + E_{waste} = \text{min!} \tag{3}$$

As a process chain consists of individual manufacturing steps, its total efficiency is determined, on the one hand, by the best possible selection of steps, and, on the other hand, by the efficiency of the individual process steps. When discussing energy required for a process step, it is important to take into account all secondary energy expenses that are required for its implementation. For example, when laser cutting is compared to punching, the punching tool has to be taken into account part of the fixed expenses $E_{fixwe,i}$:

$$E_{step,i} = E_{per\,unit,i} + E_{fixed,i} / N \tag{4}$$

Here, $E_{per\,unit,i}$ denotes the energy that is required for the processing of an individual unit and *N* is the batch size to be processed.

In the case of cutting processes like milling or turning, where material removal is the primary objective, the specific consumed energy e_{proc} and the specific processing power $p_{proc}(t)$ can be computed as objective key figures from the processing power $P_{proc}(t)$, its energy integral E_{proc}, the material removal rate $V_{rem}(t)$ and the volume of removed material V_{rem}:

$$e_{proc} = \frac{E_{proc}}{V_{rem}} \quad , \quad p_{proc}(t) = \frac{P_{proc}(t)}{\dot{V}_{rem}(t)} \tag{5}$$

This allows to compare the efficiency of different process configurations, but does not take into account objectives like surface quality.

The first element of the energy balance for which a real degree of efficiency can be given, is the machine efficiency. There, the instantaneous power required by the process can be related to the actual instantaneous power consumption of the machine:

$$\eta_{Machine}(t) = \frac{P_{Process}(t)}{P_{Machine}(t)} \tag{6}$$

The machine power consumption can be measured directly at its power input, and, in the case of chipping, the process power can be computed by multiplying force and speed or torque and turning rate. Integrating the power over the time a processing step requires, leads to the energy turnover, and, consequentially, the degree of efficiency of a machine for a process step can be quantified:

$$\eta_{Machine,i} = \left. \frac{\int P_{Process}(t)dt}{\int P_{Machine}(t)dt} \right|_{t\,\min,i}^{t\,\max,i} \tag{7}$$

Like with any theoretical degree of efficiency, the maximum attainable value of one cannot be reached by any machine.

Moreover, equation 7 highlights that the way a machine is used has an important influence on its actual energy efficiency. Typically, process power is not required continuously, while a machine consumes energy at a substantial rate even if it is standing still. Consequentially, the efficiency will be low even for highly efficient processes and machines with high efficiency components, if the machine is not switched off or put into a hibernation mode during periods of inactivity.

3. Requirements to an Energy Consumption Model

From what has been said, it can be seen that it is virtually impossible to design an optimal product, select the best process chain or ensure maximum utilisation efficiency without having detailed previous knowledge of process and machine related energy consumption. The most convenient form of this knowledge is given by a model that allows simulating the energy consumption for a large number of different scenarios. Such a model has to fulfil a number of requirements and:

- allows generic modelling of production machines,
- represents their energy consumption accurately,
- allows to make predictions for alternatives,
- is action oriented,
- can be embedded into the context of other goals,
- is lean and can be efficiently computed,
- is intuitive and easy to parameterize, and
- is scalable to the system size and detail required.

While most of these objectives might sound obvious, they are often not or not all fulfilled by modelling and simulation techniques.

4. Existing Energy Efficiency Models

Of course, the energy conversion characteristics of tool machines and manufacturing processes have been studied before.

Many engineers are familiar with mechatronic modelling and simulation for machine optimisation. While this approach could also be used for energy efficiency optimisation, the resulting models are not lean, require a large number of parameters that are often difficult to obtain, and can only be computed quickly for very simple cases. Therefore, mechatronic models are suitable only for detailed optimisation.

At the other end of the complexity spectrum lie power flow diagrams, like the one given in Figure 1, that condense energy conversion into a static representation [RAVEL/BFK 2000]. These diagrams give a general idea of the efficiency of a machine, but do not take into account how the machine is actually used and do not model the effects that are linked to design alternatives. As will be shown later on, this has an important influence on the predicted energy consumption and the efficiency evaluation.

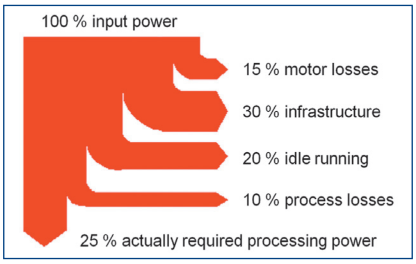

Figure 1. *Machine tool power flow diagram (Translated from [RAVEL/BFK 2000]).*

Like power flow diagrams and degrees of efficiency, many models of energy efficiency are inspired by thermodynamics [Sekulic 2006]. These are typically helpful in determining the theoretical minimal energy required for manufacturing tasks as well as for detailed modelling of the energy conversion processes. Unfortunately, they are often of limited practical use as many required parameters are unknown.

Some more specific models are available in the manufacturing sciences literature. Draganescu et.al. have introduced a detailed model of the specific energy consumption for milling manufacturing processses [Draganescu 2003]. They establish the dependencies between the process efficiency and all major cutting parameters and take into account, that the energy consumption of a tool machine is dependent on the process force in a nonlinear fashion. This is an excellent basis for further study, but cannot easily be generalised for other process and machine configurations. Moreover, supplementary aggregates of the machine are disregarded, even though these often have a major impact on the overall energy balance, as will be shown later.

A modelling framework that is able to take into account all elements of a production and even an entire enterprise is given by the International Performance Measurement and Verification Protocol (IPMVP) that is provided by the Efficiency Valuation Organisation (EVO) [IPMVP 1997]. This guideline is meant to be applied in overall energy efficiency analysis and today has been adapted and developed by many consulting agencies. For the optimisation of machine tools, though, it is of limited use, as it does not provide detail beyond key figures and does not foresee simulative case studies.

5. Machine Energy Consumption Model

From the previous paragraphs it has become clear that an improved modelling technique is required for energy efficiency assessment in the tool machine industry. Such a model, which satisfies the requirements stated in section 3, will be presented in this chapter. It is inspired by the structure of the typical machine power input measurement from a simple aluminium milling operation shown in Figure 2.

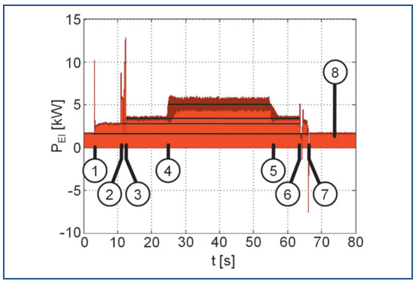

Figure 2. *Actual power input at machine main connection over time (integral area = consumed energy).*

There, a number of events can be seen to change the power intake between a number of clear cut levels. First, the coolant is switched on (1) and the machine executes a rapid motion to its starting position (2). Then the spindle speeds up (3) and the tool enters the workpiece (4). Upon termination of the cut (5), the spindle (6) and the coolant (7) are switched off. A substantial idle power intake remains after that (8).

The power consumption profiles for other manufacturing operations are similar. We note that acceleration and deceleration are only directly responsible for peak power. Although the manufacturing process does lead to a variation in the power input, its cumulated energy is considerably smaller than that e.g. of the idle power. From these considerations, we derive that the power consumption of the machine varies mainly with the operating state. The state/transition graph of the tool machine is given in Figure 3, and the corresponding power consumption of the machine components per state is shown in Figure 4.

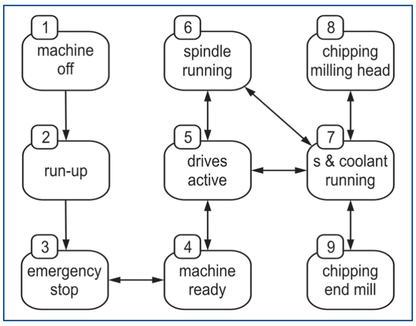

Figure 3. *State/transition model of a tool machine.*

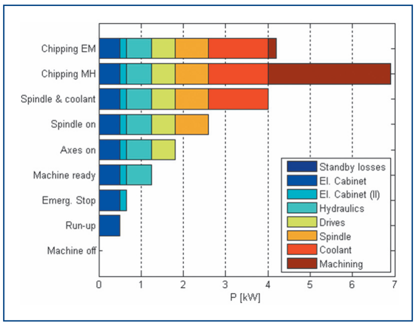

Figure 4. *Power consumption of the tool machine components in each of the states of Figure 3.*

It is emphasised that this model can be parameterised from a few basic measurements. Moreover, only two static levels of process related power consumption, end mill (EM) chipping and milling head (MH) chipping, are included and acceleration effects are not included.

This model is lean and can be evaluated in simulation with very low computational requirements. Its form is intuitive and allows for the generic modelling of many production machines. Most importantly, it is action oriented in that it takes into account how the machine is being used and allows to make predictions of the energy consumption resulting for a changed usage profile or modified components.

6. Energy Consumption Forecasting

Forecasting the energy consumption with the model introduced in the previous paragraph requires the formulation of a usage profile. This is straight forward and consists of taking note of the points of time when the machine changes its operational state. An example for a roughing operation is given in Figure 5.

Such a usage profile can for example be established offline using a numerical control program simulation. As an alternative, machine signals may be used to determine transitions between states.

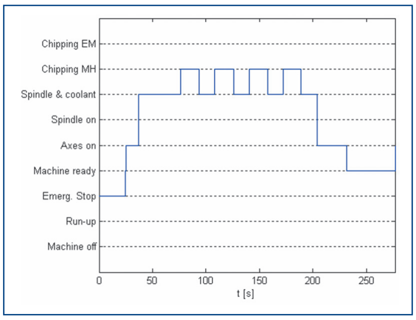

Figure 5. *Usage profile for a roughing operation.*

To evaluate the prediction capability of the model for a milling machine, we have first adapted and parametrised it in different levels of detail using a number of test cycles and then manufactured the steel workpiece shown in Figure 6. During the milling, the power consumption P_{real} at the machine main connection has been recorded and compared to the power consumption profile predicted using the models (Figure 7).

Figure 6. *Example workpiece used for the evaluation.*

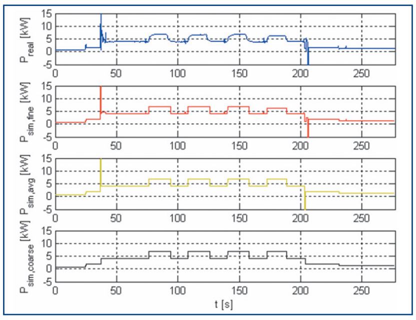

Figure 7. *Measured (top) and predicted power consumption profiles for different levels of detail.*

It can be seen that the most detailed version of the model tracks the power consumption accurately ($P_{sim,fine}$) while the model introduced in section 5 seems to give only a crude representation ($P_{sim,coarse}$). Nevertheless, even the coarse version of the model approximates the real

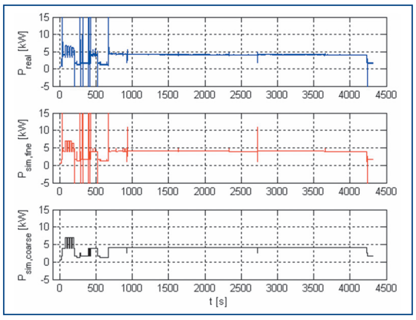

Figure 8. *Measured (top) and predicted power consumption for manufacturing the entire workpiece.*

energy integral to within 5 %. The same applies to the simulation of the entire manufacturing of the workpiece from Figure 6, with the results being shown in Figure 8. These results make it clear that the model presented in this paper is able to represent the energy consumption of the tool machine accurately.

7. Applications of the Model

As has been shown so far, it is relatively easy to predict the energy consumption of a machine tool using the model presented in this paper based on a small number of measurements. Due to the structure of the model, it can be used for a number of energy efficiency analysis and optimization tasks.

a. Model based Efficiency Analysis

As the power intake is given for each state and each component, it is easy to perform an analysis of the share of energy that each component is responsible based on the model. To do that, the power consumption of each components is computed and integrated and then divided by the total consumed energy. The result for the roughing operation is shown in Figure 9.

From this, it can be seen that despite the high mechanical power required by the milling head, the machining operation itself is responsible for only about 20 % of the energy consumed during the entire operation. This is due to the fact that the tool is not all the time actively milling on the workpiece. That the manufacturing process is responsible for only a small proportion of the energy consumption becomes even more obvious when considering the entire manufacturing of the workpiece (Figure 10).

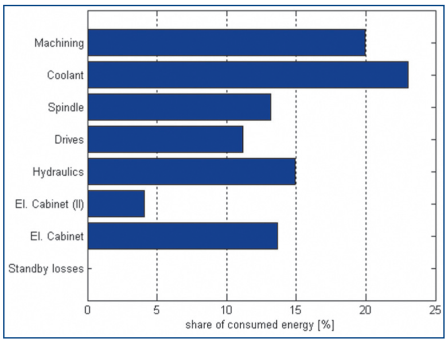

Figure 9. *Share of energy consumed by each component only for the roughing operation shown in Figure 5.*

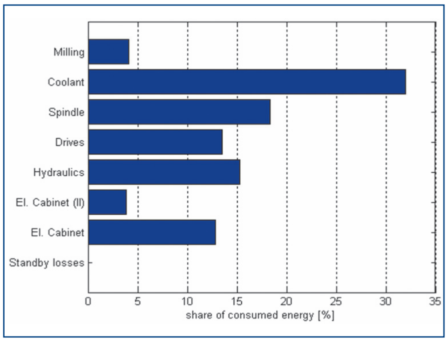

Figure 10. *Share of energy consumed by each component for the entire manufacturing of the part.*

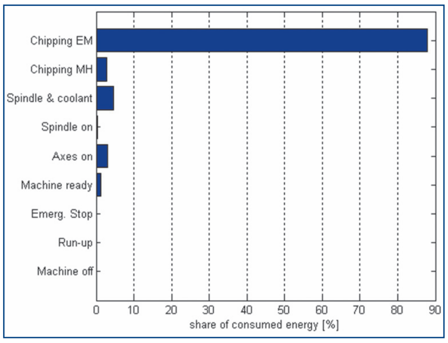

Figure 11. *Share of energy consumed in each state.*

Here, the end mill applied for manufacturing the logo used only a small proportion of the potential spindle power of the machine. This leads to low efficiency, even if milling was active most of the time (Figure 11).

Analyses like the one shown here are important tools for finding the potential for energy efficiency optimisation, e.g. by reducing idle running losses [Kuhrke 2008].

b. Component Case Study

Once the strengths and weaknesses of a machine have been determined with such an analysis, case studies can be performed on the model.

In the example given here, the available spindle power most of the time was not used to full capacity due to the limited forces the end mill could take. Only the roughing with the milling head used a large proportion of the power available, and this operation was responsible for only a small proportion of the overall energy turnover. It is therefore an obvious option to replace the spindle with a lower power unit, as the losses are typically proportional to the rated power. Such a scenario can be simulated using the existing model by reducing the spindle idle electrical power losses (Figure 3) while lengthening the time spans the machine takes for high power operations in the usage profile (Figure 5). In that way, criteria are established about how much the losses have to be lower for a reduced power spindle that still satisfies the process conditions to realise substantial energy savings.

While the experimental case study by Weisbecker [Weisbecker 2008], who replaced the spindle of an existing machine with a lower power unit and measured changes in time and energy, yields similar results, it is more expensive than the simulative study using the energy consumption model. In addition to that, the optimal configuration cannot be found experimentally due to the typically limited number of physical spindles available.

c. Operational Case Study

The second obvious conclusion that can be drawn from the analysis introduced in section 7.1 is that the coolant supply is responsible for the major part of the energy consumption. Based on the energy consumption model, the numerical control program and the selection of an equivalent dry milling process, the changes in manufacturing time and energy consumption can be computed. Here, it has to be kept in mind that any extension of the milling time means that all other power consuming units of the machine are running longer and, and some point, will eat up the savings from switching off the coolant.

8. Extensions to the Model

One of the main advantages of the model is that it can be extended with additional sub-models easily.

a. Manufacturing Process

As the manufacturing process has a major influence both on the attainable processing time and the instantaneous power drawn by the machine, it motivates the first extension of the model. This can be done straightforward by replacing the static levels of process induced power consumption in Figure 3 by a functional description depending on the machining parameters, like the one shown in Figure 12. As the tool-workpiece combination is crucial for this function, it is convenient to encapsulate this into an interchangeable module. Such a module could also include process limitations, stabili-

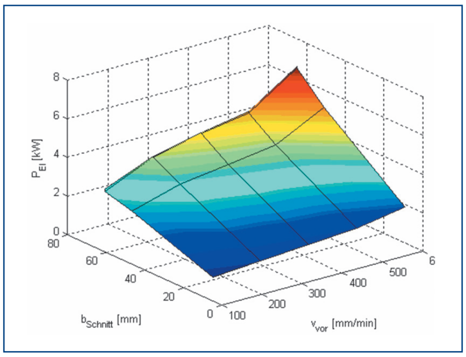

Figure 12. *Required electrical power as a function of cutting width (bSchnitt and feedrate (vvor).*

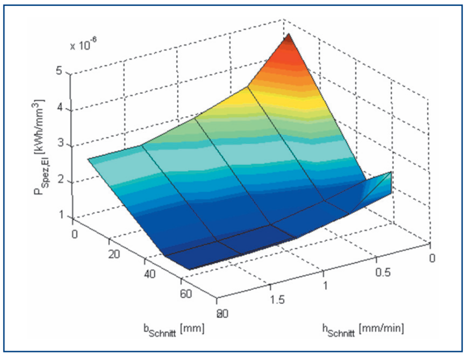

Figure 13. *Required specific electrical power (power divided by material removal rate) as a function of cutting width (bSchnitt) and cutting height (hSchnitt).*

ty and the material removal rate, which can then be used to find the optimal settings for minimum specific electrical power and energy (Figure 13).

b. Acceleration Forces

The second effect to be taken into account consists of the dynamic acceleration and deceleration forces. While the measurements introduced in section 6 make it clear that these do not contribute a large proportion of the energy consumption integral, they determine the peak power requirements and, via the rated power, the energy losses linked to the electrical machines.

Based on a kinematic machine model, moving masses and the motor power constants, it is easy to compute the instantaneous power drawn due to acceleration. This sub-model can be refined, if information about the dynamic behaviour of the machine is available in the form of bandwidth, frequency response, transfer functions or differential equations.

This model extension allows analyzing the energy savings that can be gained by using mass reduction techniques, like those studied in the EcoFIT project [Sekler 2007].

c. Hierarchical and Stochastic Models

In addition to refining the model proposed here by including more detail, it can also be extended to span all levels from the production line down to the individual components of a machine [Dietmair 2008]. Normally, this would lead to combinatorial explosion of the number of system states, but can be tackled by hierarchic modelling and abstraction. In that way, it is ensured that the model is scalable to system size and detail required.

For optimisation, usage scenarios can also be given in the stochastic form of semi-Markov processes [Dietmair 2008]. These have been used for optimisation of the control of small battery powered systems [Qiu 1999].

9. Conclusions

In this paper, a modelling framework for tool machine energy consumption forecasting has been presented. A number of examples have been given how this can be applied for energy efficiency optimisation. Future work will be directed towards extending this methodology, optimisation and merging with numerical control simulation to provide strong tools for the digital factory.

References

[Abele 2003] Abele, E.; Hermenau, U.; Feickert, S.: Methodology for the Life Cycle Inventory of Machined Parts During the Product Development Process. In: Hon, B. (Ed.): Design and Manufacture for Sustainable Development, pp. 147-151, 2003.

[Dietmair 2008] Dietmair, A.; Verl, A.: A Generic Energy Consumption Model. Proceedings of FAIM 2008.

[Draganescu 2003] Draganescu, F.; Gheorghe, M.; Doicin, C.V.: Models of machine tool efficiency and specific consumed energy. Journal of Materials Processing Technology, Vol. 141, pp. 9-15, 2003.

[Kuhrke 2008] Kuhrke, B.; Rothenbücher, S.: Vermeiden von Stand-by-Zeiten verbessert die Energieeffizienz von Maschinen. MM, No. 31/32, pp.32-34, 2008.

[Meadows 1972] Meadows, D.L.: The Limits To Growth. Universe Books, 1972.

[Qiu,1999] Qiu, Q.; Pedram, M.: Dynamic Power Management Based on Continuous-Time Markov Decision Processes", Proceedings, 36th ACM/IEEE conf. on design automation, pp. 555-561, 1999.

[Sekler 2007] Sekler, P.; Dietmair, A.; Dadalau, A.; Rüdele, H.; Zulaika, J.; Smolik, J.; Bustillo, A.: Energieeffiziente Maschinen durch Massenreduktion. Werkstattstechnik, Vol. 97, No. 5, pp.320-327, 2007.

[Sekulic 2006] Sekulic, D.P.; Sankara, J.: Advanced Thermodynamics Metrics for Sustainability Assessment of Open Engineering Systems. Thermal Science, Vol. 10, No.1,pp.125-140, 2006.

[Weisbecker 2008] Weisbecker, L.: Energieeinsparpotenziale bei Werkzeugmaschinen. Internationales Branchen- und Technologie-Symposium Energieeffizienz in der Produktion, Düsseldorf, April 1, 2008.

[Welcker 2008] Welcker, C.M.: Internationales Branchen- und Technologie-Symposium Energieeffizienz in der Produktion, Düsseldorf, April 1, 2008.

[2005/32/EC] N.N.: Directive 2005/32/EC of the European Parliament and of the Council, July 6, 2005, available from: http:// ec.europa.eu/enterprise/ eco_design/dir2005-32.htm, 2005.

[IPMVP 1997] N.N.: International Performance Measurment and Verification Protocol (IPMVP), Efficiency Valuation Organisation, San Francisco, 1997.

[RAVEL/BFK 2000] N.N.: Typischer Energiefluss einer guten Produktionsmaschine. RAVEL/BFK, 724.397.12.54 D, available from http:// www.energie.ch/themen/ industrie/infel/ maschinen.htm, 2000.

[Working Plan of the EcoDesign Directive 2007] N.N.: Study for preparing the first Working Plan of the EcoDesign Directive. Report No. ENTR/06/ 026, available from http://ec.europa.eu/enterprise/ eco_design/finalreport_wpstudy.pdf, 2007.

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