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Rapid Assessment: Method to Configure Energy Performant Machine Tools in Linked Energy Systems

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Abstract

Industrial enterprises are increasingly driven to tap the potentials of energy efficiency in existing and future production sites. The challenge is to identify cost-efficient investments for lowering the energy demand. General recommendations for the implementation of specific energy efficiency measures need a dedicated analysis of the use case of a production machine, such as a machine tool. Still users intend to find appropriate measures enhancing the energy efficiency of their production machines, while increasing the profitability simultaneously. The easy to applicate approach, which is presented in this paper, avoids costly generation and interpretation of energy data while, retaining a sufficient accuracy of the obtained recommendations for energy efficiency measures.

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1. Introduction to energy efficiency in the industrial production

Energy efficiency measures in industrial enterprises are mainly driven by significant energy costs and accordingly motivated by saving potentials. Mandatory energy assessments for non-small and medium economies, regulated in the European Energy Efficiency Directive RL 2012/27/EU, will raise the awareness of saving potentials. If the requirement is satisfied by implementing an energy management system based on ISO 50001, a continuous improvement process for energy efficiency has to be installed. As a result of the EU-regulation industrial enterprises are compelled to gain transparency on energy efficiency potentials and have to define actions to reduce the energy consumption and CO2 emissions.

Due to the advancing shortage of energy resources and the 2015 international agreement on climate action, rising energy costs can be assumed in future. Higher attention on energy consumption and escalating energy costs result both in a growing market for energy efficiency technology.

To identify cost efficient measures for reducing the energy costs of machine tools a methodical approach is obligatory. Various scientific approaches allowing the assessment of possible optimization measures were explored lately.

[1] presents a methodology which aims to assess the energy consumption of machine tools already in the machines' planning phase. The methodology is based on the use of characteristic curves of components, constituted by measurements. It is assumed that this information is available for machine tool manufacturers. By the definition of usage scenarios, it is possible to calculate the annual energy consumption of a machine tool and configuration alternatives.

A dynamic approach is developed by [2]. Using empirical data gained from datasheet information in combination with mathematical models, the developed method includes a sophisticated simulation library within the simulation environment Matlab Simulink/SimScape® retaining a high

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accuracy on the electrical power demand and the load profile. The library enables the user to build machine tool models for estimating the energy demand, using the actual NC program as input. Following a similar approach, [3] developed a dynamic simulation approach and extends the simulation models to different production machines to assess the electrical energy demand of multi-machines production process chains.

[4] introduces energy blocks. The methodology is based on the segmentation of the production process in operations, represented by consecutive energy blocks with specific energy consumption. It is assumed that similar machines for the same production task have a similar characteristic in the energy demand. The energy blocks can be based on energy measurements, simulations or approximations and corresponding mathematical approximations. The method is primarily used for production planning and scheduling. The method is not disaggregated to the component level.

A model for predicting the energy consumption of machine tools and its components based on operating states is presented in [5]. Assuming a constant power consumption of individual machine tool components in their possible operation states, the total power consumption of a machine tool is calculated by summing up the respective power consumption of the single components. The approach focuses on the optimization of existing machine tools. The power consumption of the components is determined by previous power measurements.

[6] presents a method to optimize existing production facilities based on expert knowledge, power measurements and historical production data. [7] introduces a methodology to plan and to assess the energy efficiency of a mechanical production compromising machine tools under the consideration of peripheral systems. By linking process planning, work plan and operational plan to the models, a functionality for examining various parameter constellations concerning their energetic impact has been developed. The method is based on energy data measurement and automated process data monitoring.

[8] and [9] provide an energy orientated process chain simulation approach. The procedure considers the interaction with technical building services. Connected to process parameters, which consist of process times and statistical failure data, the energy demand of the factory system is determined. To implement the method preliminary energy measurements have to be conducted. However examination is not focused on waste heat emissions of production machines and their components.

The preceding research activities reveal that a good basis for the determination of the energy consumption of machine tools already exists. However, there is only little research done to assess the machine tool as an interacting part of superior energy systems. Especially thermal power systems and the interaction with the building climate systems are considered with limited attention. The existing methods are either based on sophisticated simulation approaches or on previous power measurements.

To transfer the latest research results to industrial applications a quick-scan is needed to identify key levers. Therefore the following innovation are presented in this paper. According to the industry demand, the approach has to be (1) easy to applicate, (2) avoids costly generation and interpretation of energy data while retaining a sufficient accuracy of the obtained recommendations for (3) the electrical energy demand of a machine tool and for the (4) assumed emissions of waste heat.

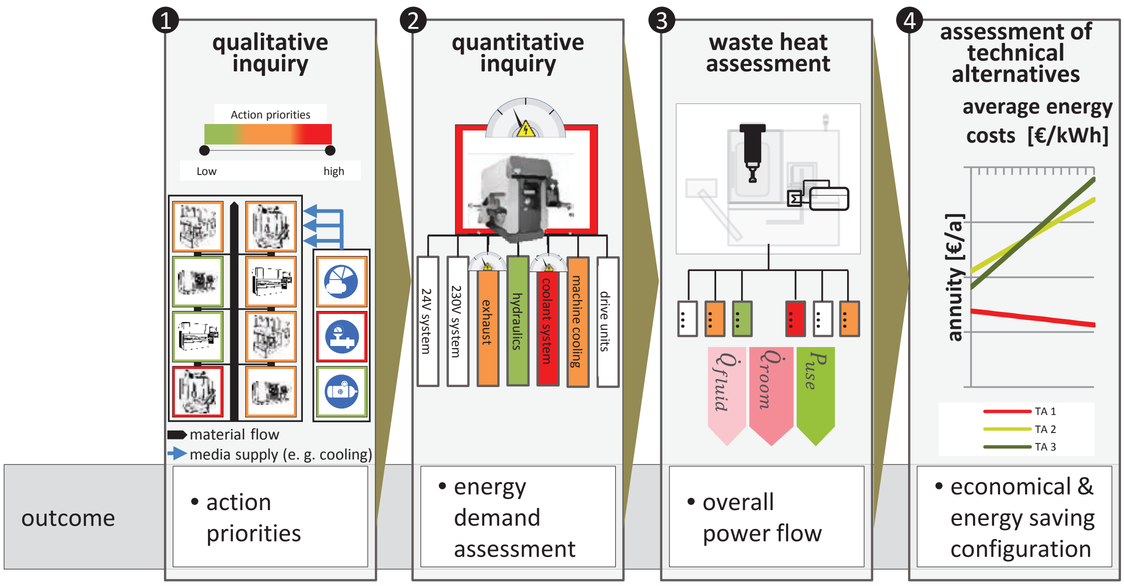


Fig. 1. Concept for a rapid assessment of energy efficiency potentials

This paper is structured as follows: Section 2 gives an introduction to the concept for a rapid assessment of energy efficiency measures compromising the overall power flow and in special the waste heat assessment. The first three of the existing four steps are introduced and the obtained results are compared with power measurements of a machine tool. Finally, the paper is closed with a conclusion and an outlook on future extensions.

2. Concept for a rapid assessment of energy efficiency potentials

The concept of the presented method, as shown in Fig. 1., is based on a four step approach and can be applied for existing productions as well as for projects in planning. To fulfil the previous described four objectives the following data sources are of major interest in existing production environments:

- Technical documentation of machine tools,
- Historical production data and future production plans [9] and
- Expert knowledge [6].

In the first step, the energy demand of a mechanical production is structured and machines with high anticipated energy saving potential are prescreened. The second step is based on the assumption that the energy demand for relevant components and its alternative configurations can be derived with sufficient accuracy based on technical documentations, production data and expert knowledge. In the third step, the waste heat emissions of the examined components and the waste heat transfer alternatives are considered. The 4th and last step supports in selecting an optimal configuration for the production machines in the context of the thermal interaction with the production building and the building services.

In this paper, the first three steps of the method are presented, which are implemented for cutting machine tools.

2.1. Qualitative inquiry to identify action priorities

To identify machine tools with a high energy saving potential a bundle of information is needed. The amount of weekly shifts of a producing business small-, medium- or large scale production is usually proportional to the load of a production machine and herewith to the load of its components [10]. Information about operating hours of the machine tool are the basis for further investigations. To assess whether saving potentials are rather high or low the power rating of the machine tool is inquired.

Operating hours can be derived locally at the production machine by operating hour counters (e.g. spindle-hours), or by a central machine data acquisition (MDA) system, e.g. out of a Manufacturing Execution System (MES). Information about the power rating can be obtained directly from the machine plate or required data are documented in the machine maintenance department.

General Machine data				Rating
Machine Number		290-06		
Manufacturer?		PTW		
Year of construction		2011		
Residual using time		> 5 years		
Power rating [kVA]		35		7
Is the machine set to a energy efficiency mode (stand-by,swiched off) outside business ours?		no		10
Total operating hours per week		168		10
Shifts (8 h) per day		3 shifts		
working days per week		6 days		
Main time/ secondary time ratio				
Average main time share [%]		45%	35,5 [h]	7
Average secondary time share [%]		55%	43,4 [h]	
	Number of work pieces produced on the machine per week	machining time [min]		
1st work piece	500	2	16,7 [h]	
2nd work piece	280	3,5	16,3 [h]	
3rd work piece	230	6	23,0 [h]	
4th work piece	170	5	14,2 [h]	
5th work piece	150	3,5	8,8 [h]	
		Total	78,9 [h]	
Non working time within operation hours per week [h]		53%	89,1 [h]	7
Total rating				8,7

Fig. 2. Identification of action priorities on relevant machine tools at the example of one machine tool

Beyond this, further data are needed as the energy saving potential is not necessarily linked to the power rating. These information concern

- Main time/ secondary time ratio,
- Machine mode outside business hours and
- Stand-by management.

To assess these data a systematic procedure has been developed involving data from technical documentations, historical production data and future production plans and expert knowledge. As the assessment uses qualitative data it has turned out to be appropriate to use a relative scale to rate the information gained in the categories described above and thus to obtain priorities for action. The scale therefore has to be calibrated in the context of the industrial production of interest, e. g. by using the results of an ISO 50001 audit.

The assessing energy expert knowledge and experience is as an integral part of the procedure indispensably, as priorities for action can differ between different production environments. The result of the procedure at the example of one machine tool is shown in Fig. 2. The result obtained by the described procedure is a sorted list with the ratings for all focused production machines of a production environment and consequently action priorities.

2.2. Quantitative assessment of the energy demand of machine tool components

2.2.1. Determination of relevant components

The starting point in order to identify relevant machine components is the determination of a component-condition-matrix. Predefined energy relevant components of the machine tool have to be analyzed regarding to their state of

Machine mode \ Component	Main Drives	HMI	Cutting lubricant pump (high pressure)	Cutting lubricant pump (low pressure)	Hydraulics	(…)
Working	On	On	On	On	On	On
Operational	On	On	On	On	On	On
Waiting	On	On	On	On	On	On
Stand-by	Off	On	Off	Off	Off	Off
Powering up	On	On	On	On	On	On

Fig. 3. Identification of action priorities within the one pre-screened machine tool

operation in different machine modes. To define energy relevant components, information about the machine tool structure and expert knowledge is essential. An established classification [11] distinguishes the following machine modes:

- Working
- Operational
- Powering up
- Stand-by
- Off

It has turned out to be appropriate to differentiate the mode 'Operational' further in the state 'Waiting'. The mode 'Powering up' usually can be aggregated usually to the 'Working' mode.

For these machine modes the state of operation of the machine tool component has to be determined. Herewith a matrix for each energy relevant component can be created (according to Fig. 3).

Of prior interest are components, which are not operating exclusively when demanded by the production process. These are components, which are running even if the machine is not set to the working mode while there is no need for specific useful energy, e. g. the unused mechanical energy output of a pump in non-working times.

2.2.2. State based quantification of the energy demand by an analytic approach

To obtain the quantitative energy demand of machine tool components further information is needed. Besides data about the working mode (e.g. pressure and volume flow for fluid pumps), information about the level of efficiency of each component is necessary. Therefore manufacturers of machine tools provide details in the manufacturer's data sheets which can be obtained from the type specification of the component. This information can be used to develop an analytic model of an individual module (e.g. pump and the associated power drive system). This model combines mathematical methods (e.g. approximation of component characteristic curves) and physical calculation methods (e.g. the first law of thermodynamic). In order to minimize the effort while generating convincing results a state-based simulation approach was chosen. This simplifies the handling and ensures the practicability of the developed method. Through the application of the method for various technical alternatives, the one with the highest energy efficiency can be identified.

The assessment of the energy demand is described in the following based on the example of centrifugal pumps which are employed in cooling lubricant systems and the machine cooling systems.

The first step is to identify the module dependent form of energy. Hydraulic power constitutes the desired form of energy for a centrifugal pump module. Hydraulic power is expressed by the product of volume flow rate and pressure (1).

$$P_{hydr} = p \cdot \dot{V} \tag{1}$$

P_{hydr} : hydraulic power demand
p : pressure
$\dot{V}$: volume flow

The input energy form of the pump itself is mechanical power whereas electrical power is the input energy form of the whole pump module including its motor. These energy forms can be translated through levels of efficiency (2), respectively (3).

$$P_{hydr} = \eta_{pump} \cdot P_{mech} \tag{2}$$

$$P_{mech} = \eta_{motor} \cdot P_{electr} \tag{3}$$

P_{mech} : mechanical power demand (pump input)
P_{electr} : electrical power demand (motor input)
η_{pump} : pump efficiency
η_{motor} : motor efficiency

The data sheets of centrifugal pumps usually contain the nominal curves of the component characteristics. For centrifugal pumps, they include pressure and pump efficiency in relation to the volume flow. The approximation of the characteristic curves can be obtained by a function of second order and a minimum of three data points. One data point of the efficiency curve represents the coordinate origin. For a centrifugal pump driven at a constant rotational speed, the pressure and efficiency are functions of the volume flow. [12] I. e. the specification of the operating pressure or the flow rate is sufficient to determine relevant parameters of energy flow. Regarding the higher attention on energy efficient technology, speed-controlled pumps are likely to gain influence. [13] At various pump speeds n, the characteristic curve of centrifugal pumps changes by the affinity laws. This dependency can be included in the approximated pump curve (4).

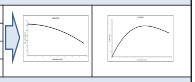
Cutting lubricant pump (centrifugal pump)			
Component data sheet			
Data points			
p_max; p_nominal; p_3			
V_p_max; V_p_nominal; V_p_3			
eta_max; eta_nominal; coordinate origin			
Component action priorities			
Working	ON		
Operational	OFF		
Standby	OFF		
OFF	OFF		
Component operating points in active component modes			
	p	V_p	
Working 1 (small tools)	10 bar	43 l/min	
Working 2 (big tools)	12 bar	12 l/min	
Pump regulation concept	Fixed speed		
Machine modes			
Working	4106	[h/yr.]	switched on
Opera-tional: Set-up / tool change	1198	[h/yr.]	switched off
Opera-tional: Waiting	2172	[h/yr.]	switched off
Stand-by	0	[h/yr.]	switched off
Time share small tools	60	%	
Time share medium tools	0	%	
Time share big tools	40	%	
Overall efficiency of motor-pump-system	< 50	%	(calculated for each operation point)
Hydraulic capacity	0,2- 1	[kW]	
Energy demand	1- 1,6	[kW]	
	Needed hydraulic capacity	Electric power demand	
		Current	
Time shares: small tools	32 %	1,0 kW	
Time shares: medium tools	-	-	
Time shares: big tools	93 %	1,6 kW	
Energy demand	4750	[kWh /yr.]	
Waste head (fluid)	3980	[kWh /yr.]	
Waste heat (room)	740	[kWh /yr.]	

Fig. 4. Assessment of the actual and minimal yearly energy demand of a machine tool component at the example of a centrifugal pump

$$p_{hydr} = \left(\frac{n}{n_{nominal}}\right)^2 \cdot \left[A \cdot \left(\frac{n_{nominal}}{n}\right)^2 \cdot \dot{V}^2 + B \cdot \left(\frac{n_{nominal}}{n}\right) \cdot \dot{V} + C\right] \quad (4)$$

A, B, C: coefficients

n_{nomial}: nominal speed in data sheet
n: speed of operation point

While changing the speed n of a pump, the maximum level of efficiency can be approximated as constant [14]. Nevertheless, the curve needs to be adapted to the changed speed (5).

$$\eta_{pump} = A' \cdot \left(\frac{n_{nominal}}{n}\right)^2 \cdot \dot{V} + B' \cdot \left(\frac{n_{nominal}}{n}\right) \cdot \dot{V} + C' \quad (5)$$

A', B', C' : coefficients

Motor manufacturers are required to provide efficiencies at 50, 75 and 100 % load. However, these data are only applicable for component usage under grid conditions (i.e. for a fixed nominal speed). Consequently, efficiency characteristic maps, which provide insight into the efficiency's dependency on frequency/ rotating speed, have to be obtained at own efforts. Since this strategy is very time consuming, the efficiency's dependence of the frequency is neglected. These three data points and the coordinate origin are used to approximate the motor efficiency. The equations 1 to 5 are implemented in Microsoft Excel® so that the user is only required to enter pressure and/or volume flow data in order to obtain the calculation results. The same procedure can be conducted with technical alternatives. The result is a comparison of the prevailing component set-up with an energy efficient set-up and the assigned overall energy demand of the set-up alternatives as shown exemplary in Fig..

2.3. Assessment of the waste heat emissions of machine tool components

An energy conversion process is associated with losses (e.g. friction). These losses are emitted in the form of waste heat to the environment (conduction, convection, radiation). Larger amounts of heat are usually dissipated by a liquid cooling fluid. In chapter 2.2 it is presented how the component characteristics of a pump module can be described in an approximated model. The specification of operating states allows the determination of the energy demand and the efficiency of the subcomponents of a module. These data serve as the basis for a subsequent quantification of the waste heat. The assessment of waste heat is described in the following based on the example of the already introduced centrifugal pumps. An approximation of the heat loss of the pump unit can be acquired as described as follows: In good approximation the mechanical losses and the radiation losses of the pump unit are negligible [15]. It can be assumed that the complete heat flow $\dot{Q}_{fluid}$ is transferred to the working fluid.

$$\dot{Q}_{fluid} = P_{mech} - P_{hydr} \quad (6)$$

$\dot{Q}_{fluid}$: total waste heat of the pump unit

Fig. 5. shows the overall energy flow of a machine tool. The supplied electrical energy is converted into heat through the components of a machine tool. Drive motors of pump

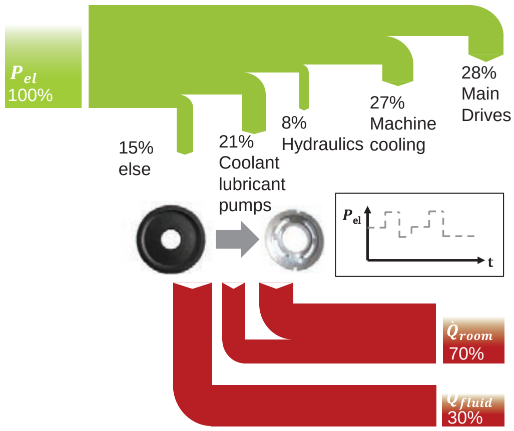


Fig. 5. Exemplary electrical energy input - and output waste heat energy flow (proportional) of a machine tool

units in machine tools are typically air cooled. Hence, the power loss over the motor unit is assumed to be transferred to the surrounding ambience air (*room*) and counts to the inner heat sources of the factory building.

$$\dot{Q}_{room} = P_{electr} - P_{mech} \quad (7)$$

The total power consumption of a machine tool in a particular machine state is calculated by summing up the average power consumption of the single function modules, according to the concept of [5]. Furthermore the amount of waste heat and information about the carrier medium is linked. Drop down menus to choose the component cooling method (e.g. air cooling or liquid cooling) were implemented to consider alternative machine tool configurations.

2.4. Validation of the introduced method

The described semi-analytic methodology introduced in section 2.2 and 2.3 was applied for validation to an EMAG VLC 100Y vertical turning machine and retains a good accuracy. When comparing the simulated waste heat in the fluid with the measured value within the respective function module, some deviations are noticeable as can be seen table 1.

Table 1. Measured and assessed data for the machine modes working and operational

Type of energy (machine mode)	measurement	assessment
P_{electr} (Working)	5.8 kW	5.7 kW
$\dot{Q}_{fluid}$ (Working)	1.4 kW	1.7 kW
P_{electr} (Operational)	3.1 kW	3.5 kW
$\dot{Q}_{fluid}$ (Operational)	1.5 kW	0.7 kW

This applies to the fact that transient effects are not covered by the state-based modelling approach. The State-based approach cannot cover dynamic effects like the cooling curve of an electric device after switching to a less energy intense state of operation. The shorter the time a machine tool remains in one machine state, the greater is the error of the chosen state-based approach. It is expected, that these short term effects have only little influence on the assessment of the aggregated yearly energy flows.

3. Summary and conclusion

In this paper, a method is introduced that can be applied to existing and planned mechanical productions, which is implemented for cutting machine tools. Therefore it fills an important gap to tap existing energy efficiency potentials in the industry. It was developed with regard to the demand for an easy to applicate approach which avoids costly generation and interpretation of energy data, retaining a sufficient accuracy of the obtained recommendations. Based on easy accessible data the method retains sufficient accuracy to assess action priorities and to obtain the energy demand of different technical alternatives. Furthermore waste heat emissions are quantified and the transfer to different media and the surrounding room is considered.

The formulation of the basic model is only the first step and will be extended by further theoretical and practical work. It will focus on the extension of the proposed method to include the waste heat emissions in an overall factory assessment. Therefore the obtained results will serve as fundamental data for a state based process chain simulation in a Siemens Plant Simulation® environment. Connected to process parameters, which consist of the determined times and time shares, the energy demand of the factory system is determined as well as the emitted waste heat flows. Those data can subsequently be used for an investigation about the efficient energy use in factory buildings. Therefore, the thermal interaction of production machines and the building including secondary consumers like systems for pressurized air, heating, air condition, ventilation will be implemented in the procedure. Furthermore, a validation of the method in industrial environments will be conducted.

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