Chapter 7
Two Practical Approaches to Assess the Energy Demand of Production Machines

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Abstract Energy efficiency becomes an increasingly important quality attribute of modern machine tools. In order to stay competitive and in liability toward our environment, the energy consumption of machine tools must be significantly reduced without deteriorating the productivity and the quality of manufacturing. In line with the rising importance, the number of available energy efficiency solutions is increasing. However, a broad application of these solutions does not exist since the hypothetical saving potentials are hard to evaluate. This chapter presents two self-developed software solutions designed for different application levels. The presented *assessment tool* allows for a quick and easy assessment of the energy demand of a given production machine and is therefore intended for utilization in the procurement process of production machines. In contrast, the *production machine simulation tool* is designed for an assessment of the energy demand in the early product development stages by providing detailed energy and power demand information for all energy-relevant functional modules as well as for the entire production machine. For both approaches, no additional hardware measurements are required as input.

7.1 Introduction

In recent years, the awareness of society, politics, and industry on the subject of energy efficiency has increased. One reason for this is the noticeable environmental impact, which yet again leads to both rising customer awareness and additional legislative regulations. The manufacturing industry, as one of the main consumers of global primary energy and producer of related emissions, represents a great lever to reduce the energy demand worldwide (IEA 2008). Furthermore, energy is an increasingly important cost factor. Within production engineering, the manufacturers

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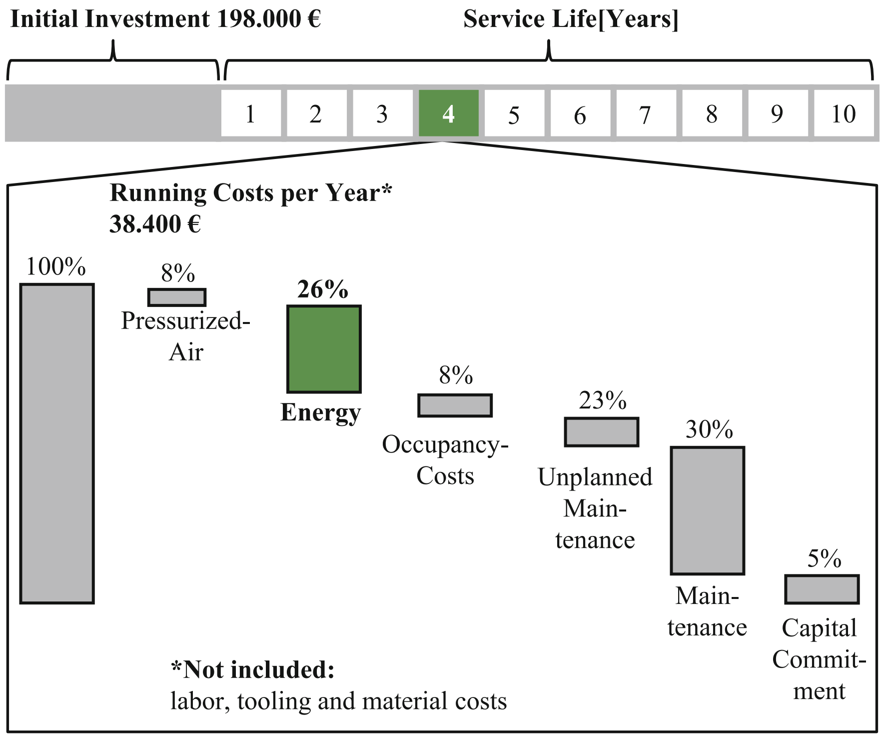

Fig. 7.1 Life cycle costs of an exemplary cutting machine tool (PTW 2008)

of production machines can notice a high customer demand for energy-efficient machines.

Studies have shown that the energy costs for machine tools are already responsible for up to 26% of the running costs—excluding labor, tooling, and material costs (see Fig. 7.1) (PTW 2008). Due to rising energy prices, this share is expected to increase further and consequently the significance of the energy efficiency factor, as one target dimension for production machines besides the classic dimensions precision, power, investment costs, and reliability, will rise (Eisele 2014; BDEW 2013).

7.2 Energy Efficiency of Production Machines

In past research, various approaches have been considered in order to optimize energy efficiency within production engineering. In the context of energy-optimized production machines, the research project "MAXIEM (maximizing the energy efficiency of machine tools)" demonstrates the maximum achievable energy efficiency. Based on the sample four-axis machining center MAG XS 211, various measures for a

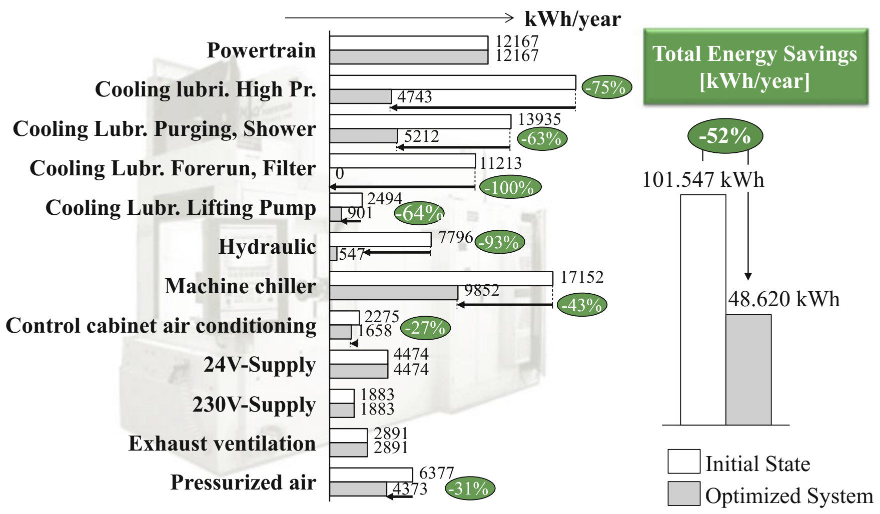

Fig. 7.2 Realized energy-saving measures on a machine tool of the type MAG XS211 (Abele et al. 2012)

component-oriented optimization and evaluation of energy efficiency have been performed. By analyzing the energy consumption of individual components, the actual delivery state of the machining center was determined. The cooling lubricant system, the machine cooling, and the hydraulic system were found to be the most energy-intensive modules. By using an energy-optimized configuration, it could be shown that energy savings of over 50% in relation to the initial state are possible. These results are based on the assumption of a mass production with a three-shift operation and six working days per week (see Fig. 7.2) (Abele et al. 2012).

7.3 Barriers for Implementing Energy Efficiency Measures

As shown in the last chapter, large energy efficiency potentials do exist. However, they are often not seized. This gap between technically and economically feasible measures and the actual implementation in industry is called the "energy efficiency gap" (Jaffe 1994). As possible reasons, *Schmid* identifies three key factors: market failures, organizational weaknesses, and inadequate possibilities for the evaluation of the economic potential (Schmid 2004).

Market failures arise if market participants are not able to include all the necessary information in the decision-making process and so do not use their resources in the most efficient and cost-minimizing way. As an example, a company might not have sufficient information about available energy efficiency measures or could be uncertain about their applicability within the company (Schmid 2004).

Deficiencies within internal company processes and corporate structure can lead to organizational barriers for implementing energy efficiency measures. For example, the energy efficiency factor might not be taken into account in the company's objectives since the focus might be on short payback periods (Schmid 2004). In addition, no tools or methods are currently available to assess the impact of an energy-saving measure. The result is an inadequate evaluation of the economic potential, which prevents investments in energy-efficient technologies (Schmid 2004).

Organizational weaknesses, market failures, and inadequate evaluation possibilities of the economic potential can be ascribed to a lack of transparency concerning energetic and economic impacts of energy-saving measures. Precisely, this transparency would be necessary to overcome the efficiency gap by using well-grounded data. One approach for this purpose is the evaluation of the energy demand of production machines by modelling their operating behavior.

7.4 Modelling the Energy Demand of Production Machines

7.4.1 Theoretical Background

Subsequently, the existing scientific approaches for both the simulation and the approximation of the energy demand of production processes and machines are presented.

7.4.1.1 Process Modelling and Machine Simulation

In the field of cutting machine tools, *Reeber* has performed basic research on energy consumption. He developed an approach which allows for the calculation of the specific cutting energy. He drew on an empirical cutting force model developed by *Victor and Kienzle*, which enabled him to determine the cutting energy depending on various process and material parameters (Reeber 1980; Kienzle and Victor 1957). The calculations do not include the energy consumption of the machine, but only the energy required for the cutting process (Eisele 2014).

Wolfram and *Degner* studied various manufacturing processes in terms of their specific energy demand. They presented an approach that complements the approach of Reeber to the additional energy demand of the machine tool. For this purpose, electrical power measurements were made in the air cut to determine the electrical idle power (all aggregates enabled, no tool contact) (Degner and Herfurth 1983; Degner and Wolfram 1983; Degner et al. 1984; Wolfram 1986, 1990; Eisele 2014).

For the first time, *Schiefer* observed the energy consumption of a machine tool in production-free periods. He assumed a constant power consumption when the machine axes are stationary (Schiefer 2001).

Gutowski developed a similar approach on the basis of electrical power measurements on various machine tools. Additionally, the energy demand of the process-specific portion resulting from the processing load and a base load is calculated. While the base load is assumed to be constant, various milling tests are carried out with varying cutting removal to determine the processing load (Gutowski et al. 2006, 2007).

Draganescu assessed the energy efficiency of machine tools by analyzing the energy effectiveness, which is defined as the ratio of theoretical cutting energy to the total energy demand. By means of statistical methods and empirical data, a mathematical model was developed mapping the relationship of various operating parameters such as spindle speed, torque, and feed rate in order to approximate the specific power consumption of a machine tool (Draganescu et al. 2003; Abele et al. 2015).

7.4.1.2 Machine Modelling and Simulation

Based on graph theory, *Dietmair* used an empirical model to predict the energy demand of cutting machine tools. For every machine component, a certain electric power demand, corresponding to the actual machine mode, was set. By specifying the sequence and the duration of the individual machine modes in the respective observation period, the power consumption and the energy need for the individual components could be concluded. Hence, it was possible to calculate the energy demand of the entire machine (Dietmair et al. 2008; Dietmair et al. 2009; Dietmair and Verl 2009; Dietmair 2010; Eisele 2014).

Bittencourt enlarged the approach of *Dietmair* by assigning a certain time and power demand to the transition between different machine modes. Both, the approaches of *Dietmair* and *Bittencourt,* neglect dynamic effects. Each machine mode is associated with a single power demand (Bittencourt 2013).

On the basis of a dynamic simulation, *Schrems* developed an approach to predict the energy demand of various production machines and processes. The production machines included in a process chain are presented by generic models. By implementing the data sheet disclosures, the energy demand of specific configurations can be assessed. As a result, the energy demand can be taken into account when planning process chains and selecting alternative production machines (Schrems 2014).

7.4.1.3 Energy Demand Approximation of Production Machines

For a prospective assessment of the energy and medium demand, *Kuhrke* developed a methodology that can already be used in the offer phase of machine tools. Therefore, a foundation for machine tool manufacturers as well as for operators for a coherent evaluation of the energy and medium demand is provided. Based on the analysis of a sample machine, he developed calculation rules for each energy-relevant component. In order to achieve this, he used both information from data sheets and data gained by measurements if the required information was not at all or insufficiently available in the data sheets. Finally, the total energy demand of the machine tool can be calculated by aggregating the individual demands (Kuhrke 2011).

In his work, *Rief* presents a predictive model for the energy demand of machine tools. As a modelling base, electric power measurements were made at various modules at different operating conditions of the production machine. For modules with process-dependent power consumption, further series of experiments were carried out at various load conditions. By means of spline curves, a characteristic model was developed which enables the calculation of the energy consumption depending on the production task (Rief 2012).

7.4.1.4 Summary

In contrast to many of the previous works, the approaches presented below do not rely on energy measurements on existing production machines. For one thing, electrical power measurements are often unsuitable in a production environment because they are associated with an increased effort and high costs, since the performance of measurements is time-consuming and the production might need to be stopped. Furthermore, measurements can usually not be used in the planning phase of a product or production due to missing physical components.

The simulation approach illustrated below allows a demand-actuated dimensioning of the modules and the selection of energy-efficient components in the product development phase of production machines. In contrast, the presented assessment tool can especially be used in the procurement process of production machines, providing a quick and easy evaluation of the energy demand of a given production machine.

7.4.2 Quick Scan: Energy Efficiency for Machine Tools

7.4.2.1 Scope of Application

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. For a final user of machine tools, a quick scan is needed to identify key levers. Conventionally, such methods are based on energy measurements of relevant machine tools and their components or on a simulation approach. An easy to applicate approach avoids costly generation and interpretation of energy data, retaining a sufficient accuracy of the obtained recommendations.

Easily accessible data are the basis of a quick scan approach. In existing production environments, the following data sources are of major interest:

- Technical documentation of machine tools,
- Historical production data and future production plans (Thiede 2011), and
- Expert knowledge (Böhner 2013).

In the following, a three-step approach is presented to identify energy efficiency measures and its economic potential:

1. Identification of relevant machines,
2. Definition of energy-relevant components and identification of discretion to act, and
3. Derivation of economic potential of energy efficiency measures.

7.4.2.2 Identification of Relevant Machines

To identify machine tools with a high energy-saving potential, a bundle of information is needed. The operational modes of a producing business small-, medium-, or large-scale production are usually proportional to the load of a production machine and herewith with the load of its components. Information on operating hours of the machine tool is the basis for further investigations. To assess whether saving potentials are rather high or low, the power rating of the machine tool is additional information to be collected.

Operating hours can be derived locally from the production machine by operating hour counters (e.g., spindle hours) or from a central registration of production data, e.g., out of a manufacturing execution system (MES). Information about the power rating can be obtained directly at the machine or is documented in the machine maintenance department.

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

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

To assess these data, a systematic procedure has been developed involving data from technical documentations, historical production data, 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.

Additionally, the knowledge of the assessing energy expert is indispensably to prioritize, as priorities for action can differ between different production environments. An example of the procedure is shown in Fig. 7.3. The result is a list of the ratings for production machines obtained by the described procedure.

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. 7.3 Identification of energy efficiency-relevant machine tools

7.4.2.3 Definition of Energy-Relevant Components and Identification of the Potential for Action

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 their state of operation in different machine modes. To define energy-relevant components, information about the machine tool structure and expert knowledge is essential. An established classification (VDMA 2014) distinguishes the following machine modes:

- Working
- Operational
- Powering up
- Standby
- Off.

It has turned out to be appropriate to differentiate the mode operational further in setup/tool change and in waiting. The mode powering up normally can be aggregated usually to the working mode.

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. 7.4 Identification of relevant components based on the component condition matrix

Based on the derived timeshares, 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. 7.4). Of prior interest are components which are not operating need-based. 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. This may be the exhaust system, the cooling fan of a decentral cooling device of a machine tool, pumps in the cooling lubricant system, or the chip conveyor.

In the following, the overall using time of each component can be calculated and the energy demand of each energy mode can be assessed. Therefore, the working mode (e.g., pressure and volume flow) as well as information about the efficiency level in the nominal operating point of the component is necessary. Additionally, appropriate assumptions have to be made which (part load) operating modes the component can be set.

The same procedure can be conducted with the technical alternatives. The result is a comparison of the prevailing component setup with an energy-efficient setup and the assigned overall energy demand of the setup alternatives derived from the methodology described and shown in Fig. 7.5.

To derive the economic potential of different energy-efficient component configurations, the average energy price has to be set as well as the target amortization time. Based on a static investment calculation, the maximal investment amount can be derived. This amount can be the basis for negotiations with component suppliers.

Cutting lubricant pump (high pressure)					
	Working	4106	[h/yr.]	switched on	
	Main time	1848	[h/yr.]	switched on	
	Secondary time	2258	[h/yr.]	switched on	
Opera-tional	Set-up / tool change	1198	[h/yr.]	switched on	
	Waiting	2172	[h/yr.]	switched on	
	Stand-by	0,00	[h/yr.]	switched off	
	Time share of cl usage during chip removal	65%			
	Share small tools	60%			
	Share medium tools	25%			
	Share big tools	15%			
	Pressure regulation concept	pressure control valve			
	Maximum pressure	50,00	[bar]		
	Volume flow	38,00	[L/min]		
	Overall efficiency of motor-pump-system	75%			
	Hydraulic capacity	3,17	[kW]		
	Electrical power demand	4,22	[kW]		
		Usage during chip removal	Needed hydraulic capacity	Electric power demand	
				Current	Optimized
Time shares	small tools	9,6%	60%	4,2 kW	2,53 kW
	medium tools	4,0%	80%	4,2 kW	3,38 kW
	big tools	2,4%	90%	4,2 kW	3,80 kW
	pressure control valve without chipping	83,9%	100%	4,2 kW	0,00 kW
	Energy demand standard system	48.899	[kWh /yr.]		
	Energy demand optimized system	5.459	[kWh /yr.]		
	Engergy costs	0,15	[€/ kWh]		
	Target amortization time	2	[yr.]		
	Energy saving potential	43.439	[kWh /yr.]		
	Max. recommended investment	13.032	[€]		

Fig. 7.5 Derivation of the economic potential of energy efficiency measures

7.4.3 Energetic Simulation of Production Machines

A popular approach in order to predict the behavior of production machines is the use of simulation models. According to VDI3633, simulation can generally be applied for technical systems within every life cycle phase: During product development, the predicted system behavior can be verified; in the use phase, potential changes to the utilization profile or retrofit measures can be evaluated in advance (VDI 2013; Abele et al. 2015).

In this context, the aim of the presented work is the development of a simulation-based assessment for the energy demand of production machines. Through the use of the developed simulation approach, production machine manufacturers as well as operators should be enabled to assess the energy demand of a production machine in an easy and standardized way. With minimal input data and most importantly no additional hardware power measurements, maximal prediction accuracy is to be achieved. Through modelling all components, relevant to the energy demand, and the energetic interconnectivity, all functional modules of a production machine are set up. Besides electrical energy, all other energy types are taken into account influencing the electric behavior (e.g., hydraulic and mechanical energy). The simulation model is implemented within the software environment MATLAB/Simscape.

The presented simulation approach covers the relevant mechanisms for calculating the energy demand of production machines. In general, the simulation structure distinguishes between three model layers (compare to Fig. 7.6) (Eisele 2014):

- **Process layer (NC code interpreter)**: Within the process layer, the interaction between the workpiece and tool is mapped. Cutting force calculations, as well as tool engagement estimations, are performed in this part of the simulation model. By transforming the calculated cutting forces into torque on the main spindle as well as forces on the feed drives, the load on the drive system of the production machine can be predicted.
- **Machine layer (machine simulation)**: Every functional module relevant to the energy demand of a production machine is mapped in the machine layer. Depending on the available data sheet information of the component manufacturer, physical/mathematical interrelationships and characteristic curves/maps are used for setting up the simulation models. Besides fixed component parameters, the model behavior depends on dynamic interactions on functional module level, process-dependent loads from the process layer, and control commands generated by the control layer.
- **Control layer (model control)**: The control layer represents the physical machine control of a production machine. Using input data from the process layer set, speeds for feed and spindle drives, as well as switching information of peripheral systems, are provided to the machine layer.

7.4.3.1 NC Code Interpreter and Model Control

The basic functionality a production machine has to offer is the desired value-adding process. All peripheral systems of a production machine support and depend on this aim. Thus, a detailed production machine simulation has to include a machining model since it builds the basis for the behavior of almost all other functional module simulation models. The developed NC code interpreter module consists of two parts (compare to Fig. 7.7). Within the *interpreter part* DIN66025 conform parts programs can be evaluated regarding

- **Switching commands**: Time or event-triggered control commands leading to binary on/off operations of functional modules or components of functional modules. An example of a time trigger command is the activation/deactivation of the

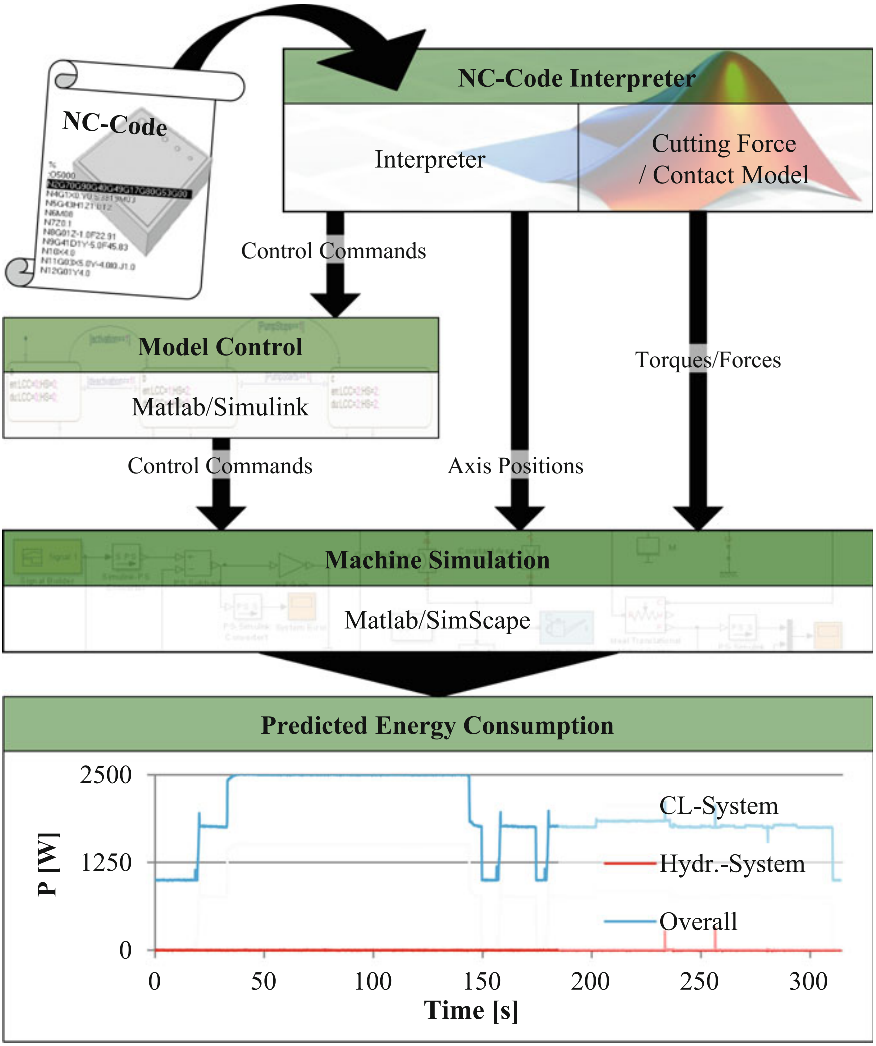

Fig. 7.6 General simulation structure

high-pressure coolant lubricant system. In contrast, a programmed tool change can lead to several event-triggered events.

- **Technology data**: Machining relevant information such as spindle speed, feed rate, and tool number.
- **Movement data**: Position data of tool and workpiece.

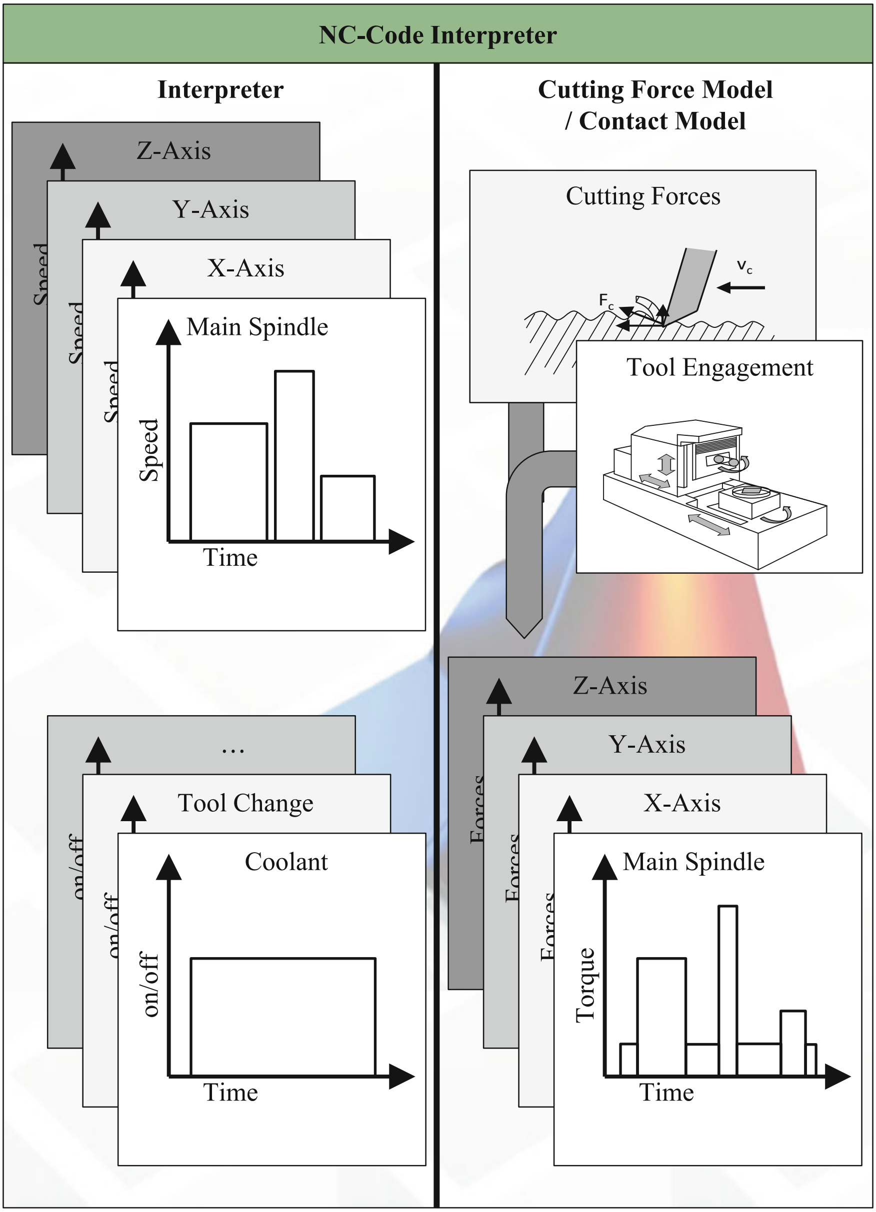

Fig. 7.7 Developed NC code interpreter

Using a plane MATLAB script with simple mathematical operations, the parts program is evaluated line by line. By combining the movement and feed rate data, time and event (axis position, switching commands, etc.) vectors are generated through interpolation.

The *cutting force/contact model* of the NC code interpreter module is responsible for calculating the cutting forces related to the machining process and for transforming them into corresponding loads on feed drives and spindle systems. Starting point for the calculations is technology and movement data extracted from the parts program in addition to geometrical and material data of the active tool and workpiece. Thus, the torque acting on the main spindle M_c can be determined as a function of the specific cutting force F_c, number of teeth in mesh z_e, and tool diameter D_{tl}:

$$M_c = F_c * z_e * \frac{D_{tl}}{2} \tag{7.1}$$

The specific cutting force F_c is obtained using the empirical model of *Victor and Kienzle* and the model extension of *Pauksch* including correcting values, e.g., for the use of coolant lubricant and different cutting materials (Kienzle and Victor 1957; Paucksch et al. 2008; Eisele 2014).

Similar to a real machine control, the model control is responsible for controlling the single functional module simulation models. Taking the extracted NC code data as input, the model control enables or disables modules, and sets limits to axis movements and spindle speed, etc. (Eisele 2014).

7.4.3.2 Machine Simulation

The main driver for the energy demand of production machines is auxiliary functions supporting the actual machining process (Abele et al. 2012). Thus, one focus of the presented simulation approach lies on the exact modelling of all functional modules relevant to the overall electric energy demand. In general, the operating behavior and thus the corresponding energy demand of all functional modules can be classified into the following three categories (Kuhrke 2011):

- Constant demand—e.g. 24-V supply and machine control,
- Cyclic demand—e.g. chiller systems and lift pumps, and
- Variable demand—e.g. main drives.

Corresponding to the operating behavior, the single functional module simulation models are set up. The input variables for the simulation model are the extracted switching commands, technology and movement data, as well as physical parameters taken from the data sheets provided by the component manufacturers (e.g. motor inductivities, characteristic curves of fluid pumps, etc.). Depending upon the available information from the modelled component data sheet, the simulation models vary.

If detailed characteristic curves/maps, representing the components behavior, are available, they are transformed into MATLAB readable lookup tables and directly

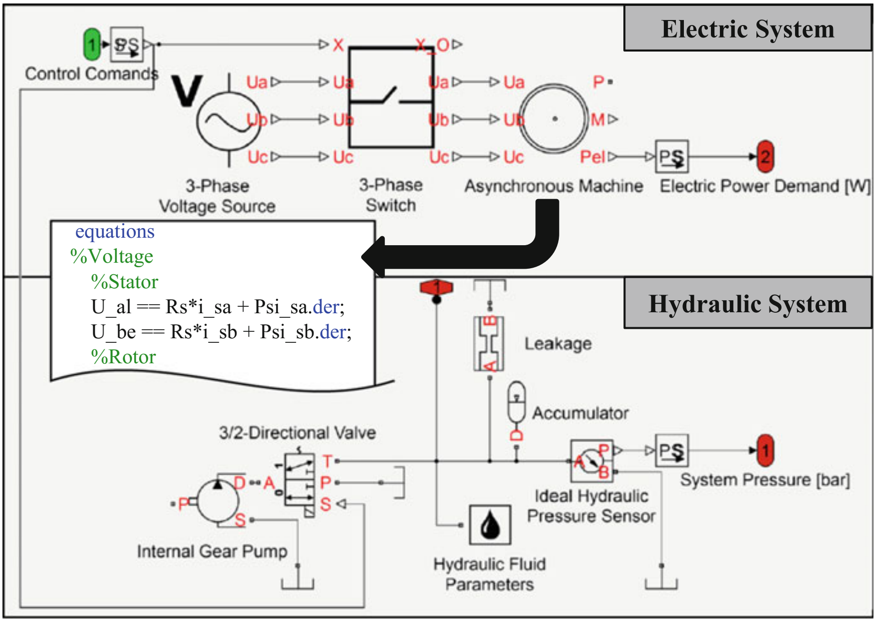

Fig. 7.8 MATLAB/Simscape model of a simple hydraulic system

used for a simulation. A common example is fixed displacement fluid pumps where often characteristic curves illustrating the relationship between acting pressure and required mechanical energy exist.

For other functional module components, such information is not available. In these cases, the component behavior is modelled using their representing physical/mathematical model. This is the case, e.g., for all electric drives.

The functional module models are implemented within the simulation environment MATLAB/Simscape. Simscape, as an extension of MATLAB/Simulink, is software for dynamic simulation of technical systems. In contrast to plain Simulink, Simscape allows modelling of physical components using an independent programming language. With its object-oriented approach, it is easy to build simulation model libraries. Simscape offers the possibility to integrate commercial MathWorks libraries for all kinds of technical systems (mechanics, hydraulics, power systems, etc.). Since those libraries are connected to additional software license costs and do not offer the needed flexibility for adaption, all simulation models on component level are developed independently. Figure 7.8 exemplarily displays a Simscape simulation model of a simple hydraulic system.

By merging and interlinking the developed component simulation models to functional modules, production machines can be mapped successively (Eisele 2014).

7.4.3.3 Exemplary Simulation Application

During the project EMC^2, the developed simulation approach was applied to a five-axis machining center which was used for titanium alloy machining in the aerospace industry. The machined part was a structural element of an aircraft belly with dimensions in length exceeding width and height by far. The machining process itself involved a multitude of different machining operations with a total duration of about 2 h. Within a first step, the main electric energy-consuming functional modules of the production machine were mapped in the previously presented simulation environment. Based on the actual parts program, the power/energy demands for all relevant functional modules, as well as the entire machine tool, were predicted.

The simulation results for a dedicated finishing operation with a face milling tool are displayed in Fig. 7.9. While the graphical results of the contact model are shown in *a*, simulated as well as measured power demand of the total machine tool is presented in *b*. During the first seconds, the drive system as well as the coolant lubricant system is switched on. The tool and workpiece engagement occur at about 22 s (simulation 8 s). The load jump between 190 s and 470 s (simulation 195 s and 450 s) is due to the chiller system of the machine tool. At 505 s (simulation 510 s), the tool retracts from the workpiece. The relative deviation between measured and simulated energy demand is less than 5% and is mainly due to differences between real occurring cutting forces and the simulated cutting forces based on an empirical model. Switching to a more advanced model could improve the accuracy. The other obvious deviation is the difference in length of the load jump induced by the chiller system. Since the chiller model is based on information publicly available from the manufacturer's data sheet, such variances can occur. By adapting the chiller parameters (e.g., real cooling capacity), the simulation results can be further enhanced.

7.5 Summary and Outlook

Due to the rising share of energy efficiency solutions available on the market, it becomes even harder to evaluate the hypothetical saving potential for a given application. Thus, there is a lack of information preventing a broad application of energy efficiency solutions. Within this chapter, several approaches to reduce this information asymmetry for production machines are presented. The chapter especially focuses on two self-developed software solutions designed for different application levels. While the presented assessment tool is designed for an application within the procurement process of production machines, allowing a quick and easy assessment of the energy demand of a given production machine, the production machine simulation tool can give detailed energy and power demand information for all relevant functional modules as well as the entire production machine. Thus, the application of the production machine simulation tool is especially intended for the machine design process. Both approaches have in common that no additional hardware mea-

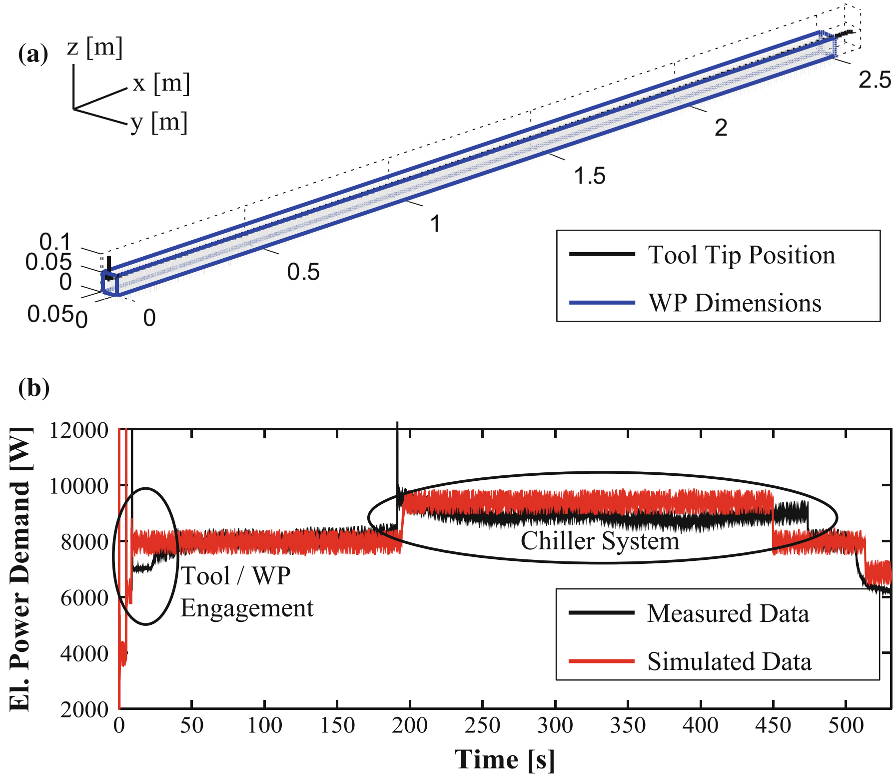

Fig. 7.9 **a** Graphical results contact model and **b** comparison of simulated versus measured power demand

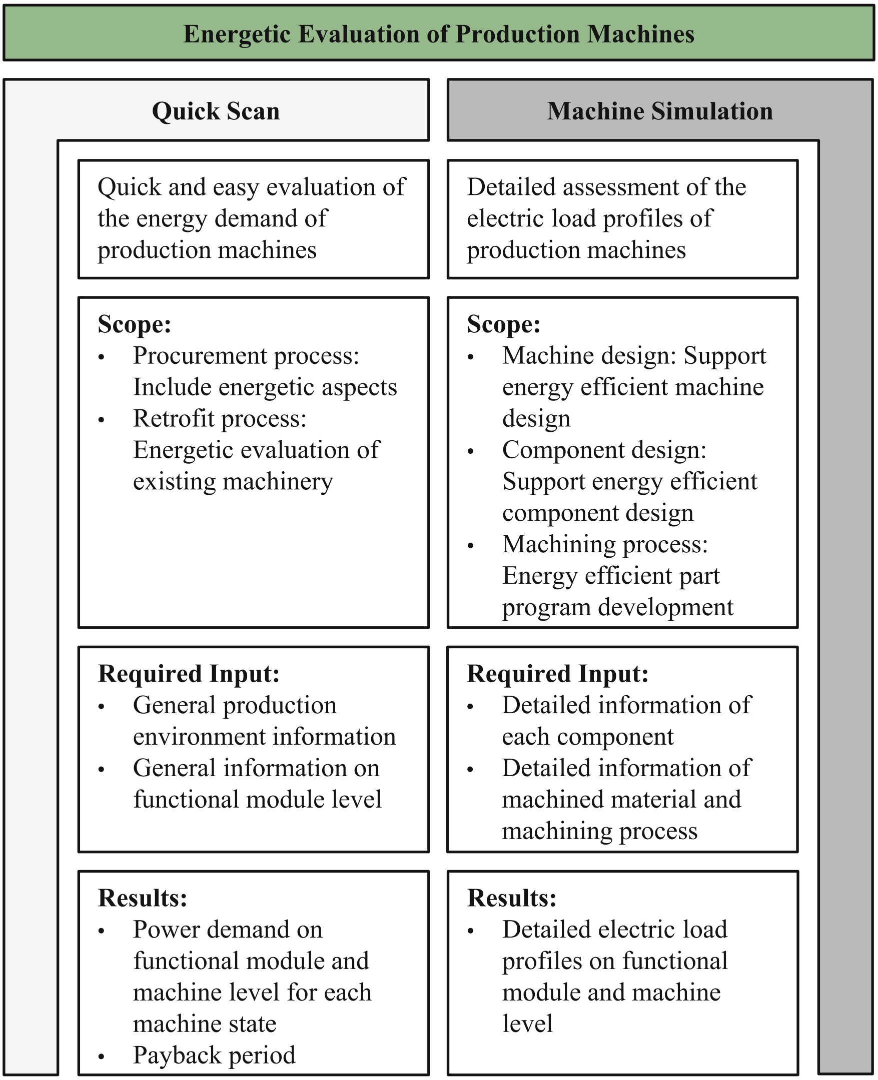

Fig. 7.10 Comparison of the two presented production machine evaluation tools

surements are required as input information. A general overview of the two presented approaches is displayed in Fig. 7.10.

While both presented approaches focus on machine and submachine level, a future application could be the simulation of an entire factory building, not only to evaluate single energy efficiency measures but to have a tool for supporting the design process of energy networks on process chain as well as factory level. For this purpose, the presented production machine simulation models need to be extended with adequate model interfaces to be connected to technical building services and factory building simulation models. By doing so, all relevant electrical and thermal energy flows within a factory can be mapped and factory system designs are tested.

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