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Energy flexible machine tool components – an investigation of capabilities

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Abstract

Besides the energy efficiency approach to reduce energy demands of production systems there are also other possibilities to decrease the energy-related operating costs. Amongst others, avoiding long-term peak loads represents a common measure in energy intensive cases. In a possible future scenario, the energy provider can also refund an energy flexible operation of factories within new tariff structures. The potential of factories and their production facilities to adapt their energy demand to shortly changing energy availability is mostly unknown. Effects of energy flexibility measures on the throughput of production machines and the quality of products are not determined as well. This paper shows a procedure to quantify the potential of technical measures suitable for production machine components using the example of a state-of-the-art milling machine. To avoid negative influence on the throughput, the measures are performed on selected machine components.

Keywords: machine tool, energy efficiency, flexibility

1. Introduction

A high reliability and low operating costs are common requirements of production systems. Nowadays the energy efficiency gains a growing importance while facing increasing energy prices and political regulations. Besides the energy efficiency, there are other possibilities to reduce the energy-related operating costs. The selective arbitrage within present tariff structures is usually limited to companies with a high demand of electricity. The reduction of peak loads represents a viable option to save energy costs in presents tariffs, available for all companies. Performing organizational measures such as avoiding parallel start-ups of machines with high-energy demand achieves a reduction of peak loads. However, with a high utilization degree of production systems, the possible time span of shifting high-energy start-ups decreases because less idle periods of production machines are available [1].

In future, the controllability of the energy demand obtains an increasing importance, caused by the growing market share of renewables that are mainly based on wind and solar power. These sources induce a high dependency of energy availability on weather conditions. To compensate the growing

dependency of the energy supply, the energy consumers (e.g. factories) can be encouraged by new tariff structures that refund an energy flexible operation.

Due to high requirements on the reliability, production systems of a high utilization ratio are up until now left out of the consideration, in spite of their big potential to adapt their power demand to the energy availability [2]. Therefore, any approach for a production system of a high utilization ratio must focus an adapting its power demand during the productive state to avoid negative influences on productivity.

In this paper a model to quantify the amount of flexible energy of milling machine tool components is described. The detailed investigation also illustrates the shifting time of the energy without influences on reliability.

2. Energy flexibility of production machines

The common definition of the flexibility of production systems is known as the capability to react quickly and with little expenses to changing conditions [3]. Therefore the energy flexibility is a property that reflects the capability to react quickly and cost-efficiently to alternating energy availability

[4]. The energy flexibility of production systems, as well of machines, can be separated into two main approaches, the technical and the organizational flexibility [5].

The measures of the organizational energy flexibility represent the ability of the production planning to schedule processes with respect to their energy characteristic. In this way, avoiding operations of high-energy processes is possible at times of a low energy availability [6, 7]. During time spans of a high energy availability an intended parallel operation is possible to benefit from low energy prices. Measures of organizational energy flexibility usually require a lead time, dependent e.g. on the frozen time interval of the production plan. Therefore current activities use approaches of short-time reconfiguration of the production schedule [8, 9].

Technical energy flexibility measures focus on a short-time adaption of the energy demand and are mainly performed within the productive state of the machine. Therefore, a machine with a higher utilization ratio raises the suitable periods to adapt the energy demand to outer circumstances. The more the machine is in operation the more application time is avaiilable. Examples for measures are a short-time adaption of the operating time of components or the changing of process parameters.

A variation of the present energy demand of the production system has usually a direct relation to the process that can lead to less throughput [2], lower quality or defective products. Thus, measures of energy flexibility have to be performed in ways that avoid any negative influence on the main processes of the machine.

2.1. Related research in the field of modeling energy flexibility

In the literature, different approaches of modeling energy flexibility exist. The methods to quantify the power adaption and the consideration of related time mainly are available for the scope of process engineering [10, 11]. More detailed analyses also estimate the benefit of measures, which can be achieved on future electricity markets [12].

In the case of manufacturing, the focus of energy flexibility research are approaches which deal with the integration of energy indicators into the production planning to achieve an energy-oriented production schedule [6, 13, 14, 15].

To quantify the potential of energy flexibility measures a state-based approach is presented by [16]. By performing different measures like the adaption of process starts or machine scheduling the energy demand can be slightly synchronized to outer circumstances. The measures are evaluated by parameters, e.g. activation time, deactivation time, minimum duration, maximum duration and costs of the measure. By a benchmarking scheme based on a user-defined scale, the measures can be compared to others on the same production system. An evaluation of the energy flexibility of entire production systems with quantified values of flexible energy is not possible. Interdependencies of linked machines are not considered as well.

A mathematical approach to estimate the energy flexibility potential of a production system is given by [17]. In the context of production theory the second derivation of the energy

demand function is perceived as energy flexibility. This interpretation allows an assessment of the resulting throughput of the production system in the case of a short-time power adaption. Therefore action alternatives can be balanced by their energy demand. The theoretical approach bases on the assumption of an one-product production system. A practical application is not given yet.

Both presented approaches focus methods to evaluate energy flexibility of production systems. How far a production machine can adapt its energy demand without any negative influence on its products and throughput is not a regarded subject. Coping those requirements is generally allocated to the users of energy flexible production systems. To what quantitative extent an adaption is possible during the productive state without influence on the throughput is not shown as well.

The model presented in the following bases upon productivity preserving measures of technical energy flexibility. It allows a calculation of the amount of the mean flexible energy of production machine components with a high utilization ratio.

3. Identification of energy flexible machine tools components

To quantify machine tool components in their energy flexibility potential, those components have to be identified which are most suitable for productivity preserving measures. An evaluating method presented in detail by [5] is used and summed up in this section.

3.1. Definition of the Energy Independency Indicator

Between all machine components direct (over control systems) and indirect interdependencies (over e.g. the process) exist in various intensities. The bandwidth of the dependency of directly controlled systems ranges from process-time independent on-off-signals to time-resolved specifications of operational parameters. The more a process is determined in time or value the less it can be adapted in these degrees of freedom and therefore be used for controlling the energy demand. The process determination by an external control system and the behavior of the components concerning their reaction to the control signals are the important factors to evaluate the Energy Independency Indicator (EII). This indicator rates the degree of independency of the energy demand to the control systems' commands by internal and external criteria [5].

3.2. Criteria of Energy Independency

The first criterion is the *external determinism* by the control systems and other components. The main processes are often controlled by high-resolution commands, whereas the most ancillary processes only receive on-off-signals. This on-off-control can also be divided into different cases, a process-cycle-dependent case which is triggered by e.g. main process events and an independent case performed with fixed time intervals. In addition to that, there are also the completely time- and quantity-controlled and the not-controlled-case.

The second criterion is called the *internal behavior* and reflects how the component reacts to the external demand and is dependent on the operational concept of the component. Different concepts are e.g. a fully in-time energy conversion (e.g. motor spindle) or a supply out of buffers (e.g. hydraulic accumulators), which are filled according to their demand. The last example provides a certain time-independency of the process and the energy demand, which is an important property for the technical energy flexibility. The definition of buffers has to be expanded to a broader field than the reservoirs for pressure or the cells for electric energy, so also other state variables, e.g. temperature values and particle concentrations can be taken into account.

3.3. Energy-Process-Independency

The energy-process-independency, determined by the external and the internal criteria, is represented by the *Energy Independency Indicator (EII)*. If a component achieves a high EII (defined in [5]) then a sufficient independency is given to consider it for measures of the technical energy flexibility.

4. System model of energy flexible machine components

Components with a high EII usually show a similar time-resolved energy demand profile. How productivity perserving measures can be performed using this property is presented in this section.

4.1. Operating states of energy flexible machine components

Considering the trend of power demand, periods in the time-resolved power demand profile of components can be identifed which respresent different operating states. During an operating state, the power demand remains approximatively on a same level. Processes with an alternating power demand are therefore modeled by an average value per operating state (cf. figure 1). All operating states can be classified as following:

- *active states*: All productive states of the component (cooling, pumping, etc.) represent an active state with a specific power demand P_A. The mean duration of the period is defined as the *mean active time* $t_{\bar{A}}$.
- *passive states*: All idle states (Stand-By, off, etc.) of the component with a specific power demand P_P and the *mean passive time* $t_{\bar{P}}$.
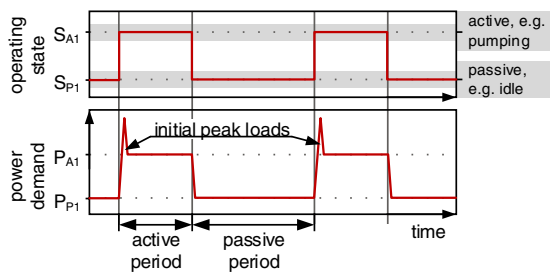

Fig. 1. Intermittent behavior of power demand.

In general, the regarded machine components change intermittently from active to passive state during operation of

the superordinated machine. The EII evaluates the dependency of the current state on the production process of the superordinated machine.

A nearly constant operating time of an active state can be generally assumed because of the fixed volumes of buffers, coolant, etc. The demands of supplies (e.g. cooling energy, hydraulic oil and coolant) are primarily influenced by the superordinated machine process. If rough maching processes with an intensive usage of coolant are predominant, the buffers have to be refilled in more frequent intervals, the passive periods become shorter.

4.2. Energy flexibility by time-wise shifting of the energy demand

The central idea of the energy flexibility model is shifting the operating time of those machine components that have no direct time dependency on the machine process. By shortening, prolonging and interchanging periods of active or passive states with respect to the requirements of the machine process, an adaption of the energy profile in time can be performed without negative influence on the reliability. The total duration of the operational states is kept constant (regarded over a larger period) so it can be assumed that the main machine process is properly supplied and therefore the productivity of the machine is ensured. Except of additional or omitted state changes with their related energy the total energy demand remains the same.

Figure 2 shows the effect of the time-wise shifting of a single active period. The unit's energy demand is interrupted by a measure (A). The interruption lasts until the state value of the component (e.g. a fill level) has reached the lower limit. To ensure an uninterrupted supply the component switches back into the active state (C). This phase is called the recovery measure and ends regularly if the state value reaches the formerly planned course (D). So the energy demand has been shifted for the time between the start of the measure and the recovery measure. This time is defined as the *energetic dead time* t_D and the corresponding amount of energy as the *flexible energy* E_F.
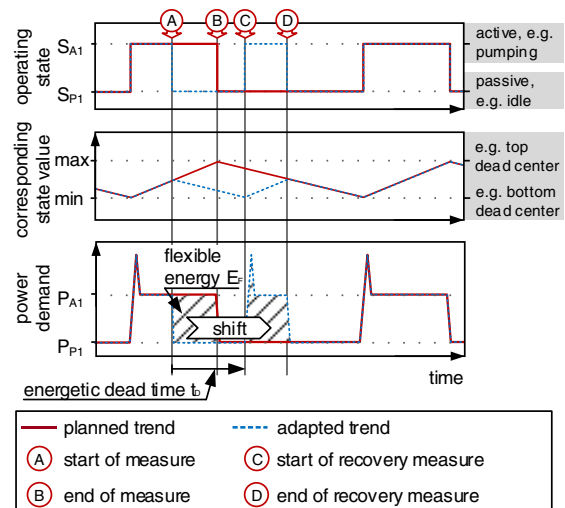

Fig. 2. Flexible energy by shifting active periods.

To quantify the flexible energy and the energetic dead time, a model is neccessary which is feasable to compare different measures and components to others in their energy flexiblity potential.

4.3. Model description

In the following, a modeling method is presented to quantify the flexible energy and the corresponding electric dead time. The model can be applied to every machine component (henceforth called *unit*) that achieved a high EII in a pilot survey.

As mentioned before a *state* is defined as a period of an approximately constant electric power demand of the regarded unit [18]. Hence the classification of the power demand profile represents a simplified image of reality, dependent on the actual scenario. For this part it can be recorded that only units can be modeled that show at least two energetic states with different power demand. Otherwise an adaption of the energy demand of that unit is not possible or just under difficult conditions.

The most simple case is represented by a unit with a defined power demand in operating (active) state and an idle (passive) state of a significantly different power demand.

4.4. Amount of flexible energy

Performing an energy flexibility measure adapts the present power demand of the unit for a specific time. Over that time the corresponding flexible energy is calculated by the difference of the planned and the actual power demand.

Figure 3 shows the reference (planned) and the actual course of a unit, adapted by a measure. In the bottom section of the figure the associated energy difference over time is shown. The plot is separated in six segments (S_0 to S_5), each of an averaged power demand.
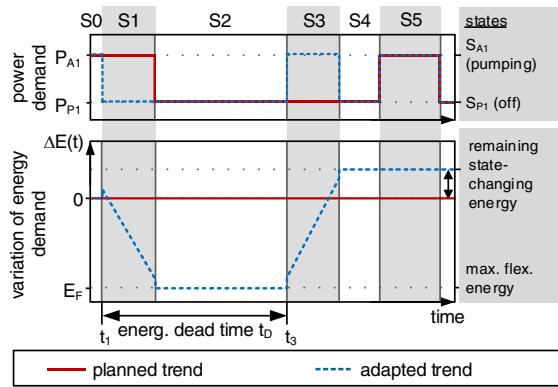

Fig. 3. Amount of flexible energy during performing a flexibility measure.

At the end of segment S_0, the planned active state is interrupted by a measure and therefore a passive state is performed. The bottom chart shows a linear trend of a growing difference of consumed energy. Within segment S_3, the recovery measure leads the value of absolute energy demand back to the formerly planned profile. A remaining difference between the total consumed energy is caused by state changing energy amounts.

The formula (1) of the energy difference $\Delta E(t)$ over time consists of three terms. The first term calculates the amount of energy out of the adapted (P_{ad}) and the formerly planned power demand (P_{pl}) within the regarded segment S_n. A possible difference E_p of the preceding segments is represented by the sum of the second term (2). The energy demand of state changes until t is included by the final term (3). Hence for $t_{n-1} \le t < t_n$ the energy difference $\Delta E(t)$ is calculated as following:

$$\Delta E(t) = \left(P_{ad}(t) - P_{pl}(t) \right) \cdot (t - t_{n-1}) + E_p + E_{\Sigma W} \quad (1)$$

with

$$E_p = \sum_{i=1}^{n-1} \left(P_{ad,i} - P_{pl,i} \right) \cdot (t_i - t_{i-1}) \quad (2)$$

and

$$E_{\Sigma W} = \sum_{i=0}^{n-1} y_i \cdot E_{W,i} \quad (3)$$

with

$$y_i = \begin{cases} +1 & \text{, if state change within adapted trend at } t_i \\ -1 & \text{, if state change within planned trend at } t_i \end{cases} \quad (4)$$

The energy difference before the start of the recovery measure (t_3) is defined as the flexible energy E_F:

$$E_F := \Delta E(t_3) \quad (5)$$

In the following section it is shown how to determine the energetic dead time t_D of the measure to calculate the required start time t_3 of the recovery measure.

4.5. Energetic dead time

To what extent the potential of a measure is capable for adapting the overall power demand of the machine depends on its beginning point. If a state is interrupted after a brief runtime a shorter energetic dead time and less flexible energy are available than in the middle or the final time span of the planned state period (figure 4). The actual points of time when the measures are initiated are arbitrary distributed over the entire state period. To calculate t_D and E_F the middle time-point of the period is assumed as the mean start time. This simplification is attended by the statistical start time of the measures, which is located at the half runtime of the accordant state period. Accordingly, after the half runtime of a period (e.g. active period: $0.5 \cdot t_{\bar{A}}$) the half of the corresponding state runtime (target state, e.g. passive period: $0.5 \cdot t_{\bar{P}}$) is available if a linear characteristic between energy demand and the state value of the unit is assumed.

In addition to the mean potential, there exist case-specific possibilities to extend this time (e.g. slight overload) [19]. Those possibilities are respected in the calculation by the factor f_P. The value of this factor is the percentage of overload and has to be defined specificly by the user (by default: $f_P = 0$). Finally the energetic dead time t_D of a specific measure M_n under consideration of the average starting time and the overload is calculated as follows:

$$t_D = (0.5 + f_P) \cdot t_{\bar{S}} \quad (6)$$

$t_{\bar{S}}$:   mean period of the target state (cf. $t_{\bar{A}}$ or $t_{\bar{P}}$)
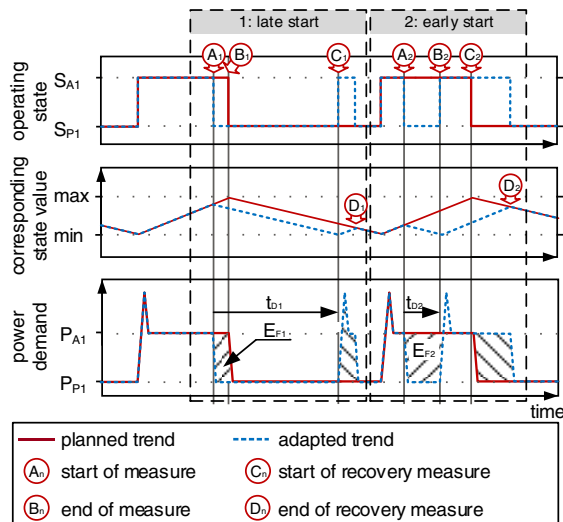
Fig. 4. Energetic dead time and flexible energy at various starting time.

By the flexible energy E_F and the energetic dead time t_D the potential of each measure M_n on any unit of a high EII can be henceforth quantified.

5. Energy flexibility potential of a machining center

In the following the procedure is applied to the components of a machining center. After classifying the EII of the components, the flexibility potential is determined.

5.1. Determination of the Energy Independency Indicator

The evaluating method to quantify the EII has been performed at a machining center. The result is shown in table 1 whereas a detailed description (including the grades of external determinism and internal behavior) is given in [5]. An EII of *plus* (+) and *double plus* (++) can be assumed as a high independency. The other grades are *mean* (o) and *poor* (-).

Table 1. EII of selected components of the machining center.

Component	External determinism	Internal behavior	Energy Independency Indicator
Spindle cooling unit	1	1	++
Coolant lifting pump	1	1	++
Low pressure lubricant pump	3	4	-
Hydraulics	3	1	+
others	n/a	n/a	less than o

5.2. Calculation of technical energy flexibility

Further analyses have been performed at the spindle cooler and the coolant lifting pump of the machining center. To obtain the necessary data, different rough machining processes have been operated with low pressure cooling on a tempered steel workpiece. Table 2 shows the determined parameters to quantify the energy flexibility potential. For this case, possible overload factors (f_p) have not been regarded.

Table 2. Selected parameters of the regarded machining center.

Parameter	Unit	Components	
		Coolant lifting pump	Spindle cooling unit
mean active power demand P_A	kW	0.99	2.93
mean passive power demand P_P	kW	0	1.20
mean active time $t_{\bar{A}}$	s	43.8	184.2
mean inactive time $t_{\bar{P}}$	s	96.2	539.6
overload factor active state f_{P_A}	-	0	0
overload factor passive state f_{P_P}	-	0	0
state changing energy $S_A \rightarrow S_P$	Ws	0	0
state changing energy $S_P \rightarrow S_A$	Ws	211	770

The mimimal runtimes of each state are not nesessary for the calculation but important criteria to decide if a measure can be executed. If the runtime of the target state is shorter than the minimal runtime, the measure may not be performed to avoid any negative influence on the component. Table 3 shows the result of the calculation and therefore the energy flexibilty potential of the regarded components.

Table 3. Energy flexibility potential of the regarded components.

	Flexible energy E_F in Wh	Energetic dead time t_D in s
Spindle cooling unit		
Interruption of active state	129.7	269.8
Early start of active state	-44.0	92.1
Coolant lifting pump		
Interruption of active state	6.1	48.1
Early start of active state	-13.4	21.9

6. Model validation

During productive state of the machining center, the coolant lifting pump has been subject to energy flexibility measures. By an additional microcontroller the operation of the pump has been started or interrupted at several random points of time. The power demand of the pump has been measured and compared to the conventional demand without measures to determine the individual flexibility parameters.

The results of several interruptions of the active state are presented in figure 5. The vertical axes show the flexible energy achieved by each test. The measured corresponding dead time until the next active period is represented by the values on the horizontal axes. The wide spreading of the test results is caused by the underlying production process of the machine and therefor the general dependency between the energy flexibility and the manufacturing process. The star represents the energetic dead time and the flexible energy calculated by the described model.
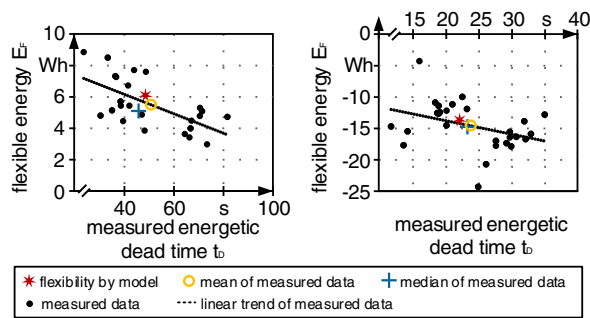
Fig. 5. Results of validation tests and comparison to flexibility model.

The model shows a good accordance of the flexible energy and the dead time compared to the mean values. A remaining mean deviation of 6,5 % can be accepted due to the high dependency of the parameters on the operated processes. Consequently, it can be assumed that the model is valid to predict the energy flexibilty potential of machine tool components.

7. Summary

In this paper a model was presented to estimate the energy flexibility potential of machine tool components without any influence on productivity. The parameters *flexible energy* and *energetic dead time* were introduced to calculate the potential of the basic measures by a few test values. Therefore machine tools can be benchmarked in their energy flexibility potential on their component level and it is now possible to estimate the energy flexibility during productive state.

Further research will focus on the consideration of multiple active and passive states and take partial load states into account. Also the transfer of the model to components of other production machines and the application to other plant levels will be a main topic of future work.

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References

[1] Yusta JM, Torres F, Khodr HM. Optimal methododlogy for a machining process scheduling in spot electricity markets. Energy conversion and mangagement, Vol 51/12 (2010), p. 2647-2654.

[2] Li L, Sun Z, Tang Z. Real time electricity demand response for sustainable manufacturing systems: Challenges and a case study. In: 8th IEEE International Conference on Automation Science and Engineering, 20.-24.8.2012, Seoul, Korea.

[3] Eversheim W. Produktionstechnik und -verfahren. In: Kern W et al. (eds.), Handwörterbuch der Produktionswirtschaft. Stuttgart: Schaefer-Poeschel, 1996. p. 1534-1544.

[4] Grassl M, Vikdahl E, Reinhart G. A petri-net based approach for evaluating energy flexibility of production machines. In: Zaeh MF, ed. Enabling manufacturing competitiveness and economic sustainability. Berlin: Springer, 2014. p. 303-308.

[5] Popp RSH, Zaeh MF. Determination of the technical energy flexibility of production systems. Advanced Materials Research 1018 (2014), p. 197-202.

[6] Pechmann A, Schoeler I. Optimizing energy costs by intelligent production scheduling. In: Hesselbach J, Herrmann C, eds. Glocalized Solutions for Sustainability in Manufacturing. Berlin: Springer, 2011. p. 293-298.

[7] Fernandez M, Li L, Sun Z. "Just-for-peak" buffer inventory for peak electricity demand reduction of manufacturing systems. International Journal for Production Economy 146 (2013), p. 178-184.

[8] Schultz C, Sellmaier P, Reinhart G. An approach for energy-oriented production control using energy flexibility. Procedia CIRP 29 (2015), p. 197-202.

[9] Shrouf F, Ordieres-Meré J, García-Sánchez A, Ortega-Mier M. Optimizing the production scheduling of an single machine to minimize total energy consumption costs. Journal of Cleaner Production 67 (2014), p. 197-207.

[10] Roos JG, Lane IE. Industrial power demand response analysis for one-part real-time pricing. IEEE Transactions on Power Systems 13 (1998) Vol. 1, p. 159-164.

[11] Karwan MH, Keblis MF. Operations planning with real time pricing of a primary input. Computers & operations research 34 (2007) Vol. 3, p. 848-867.

[12] Mitra S, Sun L, Grossmann IE. Optimal scheduling of industrial combined heat and power plants under time-sensitive electricity prices. Energy 54 (2013), p. 194-211.

[13] Junge M. Simulationsgestützte Entwicklung und Optimierung einer energieeffizienten Produktionssteuerung. PhD thesis. Kassel: university press, 2007.

[14] Bruzzone AAG, Anghinolfi D, Paolucci M, Tonelli F. Energy-aware scheduling for improving manufacturing process sustainability: A mathematical model for flexible flow shops. CIRP Annals – Manufacturing Technology 61 (2012), p. 459-462.

[15] Bonneschky A. Integration energiewirtschaftlicher Aspekte in Systeme der Produktionsplanung und –steuerung. PhD thesis. Berlin: dissertation.de, 2002.

[16] Grassl M, Reinhart G. Evaluating measures for adapting the energy demand of a production system to volatile energy prices. Procedia CIRP 15 (2015), p. 156-161.

[17] Kabelitz S, Streckfuß U. Energieflexibilität in der Produktionstheorie. ZWF Zeitschrift für den wirtschaftlichen Fabrikbetrieb 109 (2014) 1-2, p. 43-45.

[18] Dietmair A, Verl A. Energy consumption forecasting and optimisation for tool machines. Modern Machinery Science Journal 62 (2009), p.63-67.

[19] Popp R, Zäh MF. Steuerung des Energiebedarfs von Werkzeugmaschinen. wt Werkstattstechnik online 104 (2014) Vol. 6, p. 413-417.