Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 33 (2019) 343–350

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

16th Global Conference on Sustainable Manufacturing - Sustainable Manufacturing for Global Circular Economy

A practical approach to reduce energy consumption in a serial production environment by shutting down subsystems of a machine tool

Alperen Can[a,*], Gregor Thiele[b], Jörg Krüger[b], Jessica Fisch[a], Carsten Klemm[a]

[a]*Daimler AG, 040-N202, 12277 Berlin, Germany*

[b]*Department for process automation and robotics, Fraunhofer IPK , Pascalstraße 8-9 10587 Berlin, Germany*

Abstract

Energy efficiency in production is becoming increasingly important for the automotive industry, motivated by political regulations and competitiveness. Many theoretical approaches to achieve an efficient production via advanced control have only been tested in experimental environments. Important for the transfer into serial production is the proof that all requirements (e.g. quantity and quality) will be met. For ensuring production on demand, machine tools (MT) imitate the real production process to keep themselves at operating temperature. All subsystems of a MT operate at full power in this state, disregarding its necessity. Shutting down these subsystems during non-productive periods is a promising approach for saving energy. This paper will present a method for shutting down components during non-productive periods, while ensuring the ability to produce on demand. Successful tests were already performed during live operation in a plant of a car manufacturer in Berlin, Germany.

Keywords: machine tools, optimization, energy efficiency,, efficient manufacturing,, energy savivng,, machine tool

1. Introduction

Nowadays, generation and consumption of energy are a meaningful topic in the entire society. The manufacturing sector has developed a pronounced awareness over the past years. By reason: in the global consumption of electrical energy, industry has a proportion of 42% [1]. Machine tools account for a significant part, in [2] estimated to be 50% of the total amount of electricity consumption in manufacturing.

*Corresponding author. Tel.: +49 30 74 91-35 08 ; fax: +49 711 177 907 72 65.
E-mail address: alperen.can@daimler.com

10.1016/j.promfg.2019.04.042

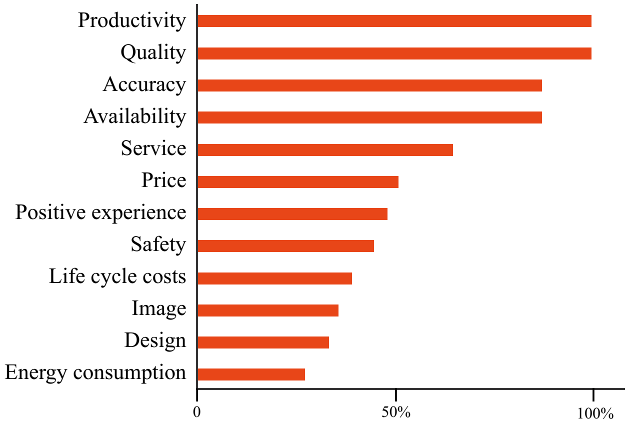

Fig. 1. Different KPI – relevance shown in length [3]

The topic of increasing energy consumption and its environmental impact is well known and is curbed by political regulations. The Energy Efficiency Directive from 2012 (2012/27/EU) includes the aim to reduce primary energy consumption by 27% compared to a reference development [4]. Nonetheless, potentials to save energy in the machine tools operation are far from been exhausted. Despite the obvious need for more efficient manufacturing, novel approaches to decreasing energy consumption, only slowly are being put into practice [3]. This is very comprehensible since traditional requirements like time, cost and quality may have reciprocal relationships with the energy behavior [5]. The estimated relevance of different aspects of production is presented in fig. 1 [3]. This motivates to consider the practical conditions of an implementation in live operation. A novel approach is presented here, corresponding to the following outline: First, some brief remarks about research towards energy efficiency in manufacturing are made in part 1.1. The part 1.2 adds some facts about machine tools, the technical context and typical conditions. Several techniques for reducing energy consumption will be presented in part 2. The focus will lie on methods which shut down auxiliary aggregates in non-operative periods. In part 3, a new approach is proposed. An experimental validation is presented in part 4, followed by a discussion of the consequential results in part 5. The conclusion in part 6 will sum up and reflect the entire study.

1.1. Potentials and strategies for saving energy in production.

In an industrial context, energy optimization can be addressed at different levels of the automation pyramid. According to [6], the following levels can be distinguished:

Global supply chain. An interesting approach is presented by Unal et al. [7]. It describes an integrated framework for energy reduction in manufacturing process chains. Components and sub-processes with extraordinary energy or resource consumption are found in energy process analysis. These data are evaluated to adapt the materials and processing of the parts according to the expected energy consumption.

Facility / Factory. In common energy analysis and optimization approaches, the various components of a complex plant are considered as isolated systems. The energy coupling is taken into account within the project *EnEffReg* [8] to find optimal set-values. An example for such optimization tasks can be found in supply technology: for an arrangement of chillers, water circulation, and cooling tower, when optimizing each component individually, the resulting optimal parameters differ from those found when optimizing the whole system .

Production line. The project *ETA-Fabrik* describes how, by tracking individual workpieces throughout the production line, predicting production utilization is made possible, thus enabling shutdowns of entire facilities. Which, in turn, would reduce energy consumption dramatically[9]. In [10], different approaches and strategies for increasing energy efficiency of a production line are presented, including preemptive proceedings like order scheduling and controlling operating states.

Machine tool. energy optimizations on machine tools are considered at either machine control level or at component control level [11]. In drilling and turning operations using appropriate tools is pivotal. Also, tool selection influences on energy and cost efficiency [10]. The project *EnEffAh* describes the use of low-friction mechanical components of an electric drive, minimization of moving masses and efficient dimensioning of electric drives.This paper will not focus on optimizing individual components but on their energy-aware control.

1.2. General properties of machine tools

Before presenting detailed techniques, it is appropriate to discuss the some fundamentals of machine tools and their context in manufacturing. Thereby, a concrete scenario from real production is introduced. Machine tools process workpieces made out of rigid materials like metal in order to achieve a desired shape, e.g. for a mechanical function. Such performing processes are be either grinding, boring, shearing or cutting. Despite the very broad spectrum of different machine tools, we can assume some commonalities – e.g. similar technical context and operational states.

1.3. Technical context

Usually, the series production of a component consists of various machine tools performing a set of tasks in specific order. Nowadays, individual processing steps are processed mostly automatically. Therefore, the timing of the chained operation is of great importance, since each individual station is dependent on its predecessors and successors. Accordingly, the main focus lies on technical availability of each individual machine tool in order to minimize logistic disruptions in the value chain. This includes to avert violation of quality requirements in single processing steps. In order to avoid such disturbances, the machine tools are kept in simulated processing cycles during non-productive periods. This so called warming up program ensures maximum availability. The validation of the cycle time is taken from the Programmable Logic Controller (PLC). In regular operation, counterchecks within established intervals ensure that all quality requirements are met.

1.3.1. Operational states

Based on the ISO14955-1: 2012, the operating states of a machine tool are to be presented. Eberspächer refers to the standard and assigns the operation of a machine tool to the respective operating modes of a machine tool [12]: Measurements in live operation allow to classify the energy level of operational states in fig. 3. The *green phase* describes a usual production state with small amounts of logistic problems.

Operational States	Switching states				
	Mainswitch	Machine control	Aggregates	Axle drives	Main spindle
Operation	ON	ON	ON	ON	ON
Ready to operate Warm up	ON	ON	ON	ON	ON not rotating
Standby	ON	ON	ON	OFF	OFF
Disorder	ON	ON	OFF	OFF	OFF
Machine off	OFF	OFF	OFF	OFF	OFF

Fig. 2. Overview of operational states [12]

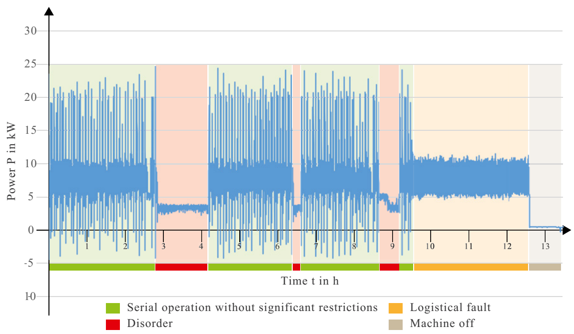

Fig. 3. Overview of operational states and power level of MT

So it could be associated with the mode *Operation* in fig. 2. The *red phase* is an disorder state, where the Programmable Logic Controller (PLC) and the Main-switch are on. The *yellow phase*, caused by logistical irregularities, draws large amounts of power without actually producing any work pieces. This is an unproductive state, which could be caused by missing processing parts or an occupied outlet. In fig. 2, this state would refer to the mode *Ready to operate / Warm up*, where all of the systems are basically turned on. This state allows the MT to produce on demand, if the fault is canceled.

1.3.2. Typical measurement equipment

Relevant production data is recorded on different levels. Machine states and cycle times are read from the PLC. Despite possibilities for in-process quality data acquisition, most production managers access external measuring equipment. The electrical power of a MT is observed using measuring devices, such as *Siemens Sentron Pac3200*.

2. State of the Art

These days, awareness of the imperative to save energy and resources is discernable in many different ambitions.

2.1. KPI for efficiency assessment

For judging about the efficiency of systems, a clear set of measurable indicators is paramount. Key performance indicators are formed to give meaningful, intuitive statements about the performance of a system or process. Definitions for such indicators should be general enough to guarantee comparability of different systems but also specialized enough to cover all relevant properties. Strategies for defining such indicators are given in [13]. To formulate efficiency as the ratio of a benefit and an energy effort, this output reference has to be defined.

2.2. Practical approaches for energy efficient control of machine tools

In a case study for a machine tool, coolant related equipment was identified as the major energy consumer [14]. As inference, the pumps were concentrated in a single unit and the pressure was optimized. This resulted in energy savings of 26%. Additionaly, the inverter frequency was adjusted. These changes led to a reduction by 42%.

ECOMATION. Significant research in the field of optimizing machine tools was done in context of the ECOMATION project [15]. A classification of energy consuming components of a machine tool is presented in [16]. This results in a generalised, modular model of several hierarchical levels. For example, a machine tool has a property *main spindle* from which an underlying property *motor* leads to a specification of the motor type (synchronous motor / DC motor / asynchronuous). All these sub-modules are described regarding their energy-related behavior using the Energy Information Description Language (EIDL). This language considers not only the models but also further control information. Energy measurements are included as well as current states of components like *pump on / pump off*. A third set of parameters/variables describes the conditions and restrictions for degrees of freedom to reduce energy consumption - so called *adjusting levers*. It describes the energy and time it takes to switch the component, contains a prognosis regarding the power consumption in the follow-up state. Describing the analyzed system in this way, the behavior of machine tools can be understood, predicted and optimized as an ensemble of interacting components. In [17], the optimization problem is modeled as a graph. The available operation modes are represented by nodes and related transitions are represented as edges. Each edge is assigned a weight, representing the energy effort for chainging the state. Dijkstras $A^\star$ algorithm is used for choosing state transitions which reduce the overall energy consumption.

Project Maxiem. Abele did comprehensive research on optimizing energy efficiency of tool machines. At project MAXIEM in [18], the energy behavior of subsystems were analyzed. Tests with shut downs of subsystems during non-productive periods were performed at a prototyping machine, which was not in serial production. The transfer to series production is a central matter of this paper.

3. Approach

In part 1.1 we stated the rigid restrictions of daily serial operation. Accordingly, it is necessary to validate these targets continuously during testing. During interruptions due to logistic faults, the MT rests in warm up state, with switched on ancillary units, main switch, control, and axle drives. We aim to exploit this potential.

3.1. Identification of suitable aggregates

The following identification is based on an expert interview. The first interviewee is the operating engineer who is responsible for the production line. The second interviewee is a machine design engineer at the MT manufacturer. In order to identify the right subsystems to turn off without affecting the main KPI's, the components of the MT have to be analyzed. Like depicted in figure 4, a typical MT includes five ancillary units: the main spindle, and various axle drives. The pneumatic compressor will be neglected in case of this study, because the compressed air is provided centrally in the concerned plant.

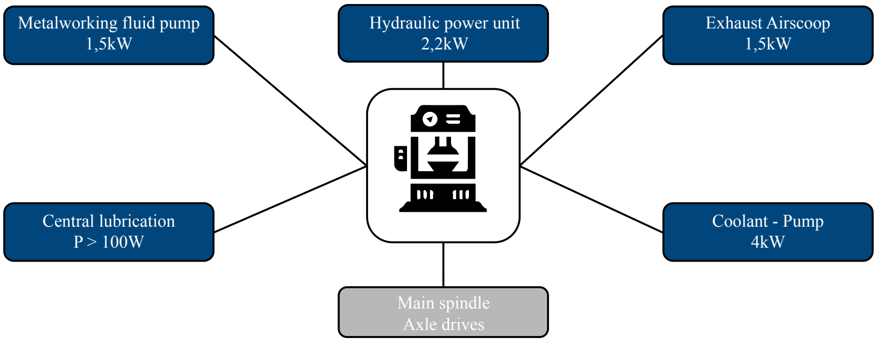

Fig. 4. Example aggregates of a MT

The main spindle and axle drives will not be considered to avoid critical effects on the process. In order to determine shutdowns of ancillary equipment in non-productive states, the functional areas of the respective aggregates must be analyzed. An expert interview was conducted on the functionalities and significance of the ancillaries.

Hydraulic unit. The hydraulic unit regulates the pressure of the hydraulic oil, which is necessary for the movements and the fixing of grippers and axles. According to the imitated production process during the stand-by state, the axles and grippers are moving. So shutting down of this subsystem is not appropriate.

Air conditioning unit. The air conditioning unit is responsible for the compensation of process heat and power dissipation of the electric drives. Due to the active axle drives and the rotating main spindle in the warm-up program, it appears to be inappropriate to switch off this unit too.

Cooling lubricant unit. The cooling lubricant unit is used to remove the chip from the component during the chipping process and to cool the tool of the MT. Since there is no chip in the imitated process and the tool does not touch a component, neither the cooling of the tool, nor the removal of chips is necessary. Accordingly, it makes sense to turn off the cooling lubricant unit.

Exhaust air unit. The exhaust air unit, which treats the exhaust air of the cooling lubricant unit can consequently also be turned off without hesitation.

Central lubrication unit. The central lubrication unit consumes at low power and operates only periodically, so that this unit can be neglected.

3.2. Adjusting the duration of power-off periods

Due to short logistic disturbances and the dynamic behavior of electrical drives of the ancillary units, a well thought out dimensioning of the time buffer up to the shutdown is required. Furthermore, the aspect of wear of the electric drives must not be neglected. Statistical evaluations over one month showed that the logistic faults last at least 50 seconds, usually longer. These disturbances over 50 seconds take place up to 20 times within 24 hours.

Studies considering the dynamic start-up behavior of electric drives let conclude that the drives must remain off for 30 seconds on average to achieve energy savings. The datasheets of the electrical drives state that an average of up to 50 shutdowns per 24 hours is permitted before oberving enhanced wear characteristics. After shutting down, a waiting time of $t = 120s$ is recommended to avoid complications.

3.3. Tool to shut down auxiliary units, practical implementation and usability

Shutting down the ancillary units in predefined operating states is realized by a PLC function block, called *Standard-Energiemanager*. The logic of the block is shown in figure 5. There is no need for additional hardware. When a desired state is active, the function block will wait out the configured time and check the predefined operational terms like *no disorder*, *safety doors locked* and *machine was in a serial operation before*. If these terms are valid, the configured aggregates will be shut down. Once the unproductive state is over, the aggregates will start up immediately, triggered by a separate function.

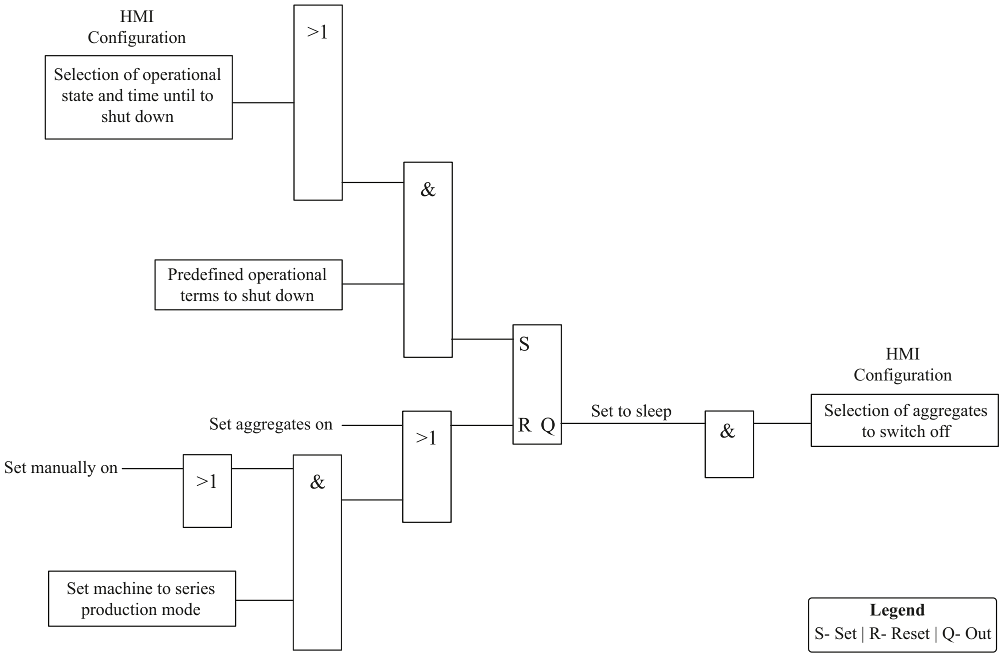

Fig. 5. Schema of the function block *Standard-Energie-Manager* with logic elements: OR(> 1), AND(&), RS-FlipFlop

4. Experiments

The presented approach was tested on a turning milling center of the brand EMAG. The MT has an electrical power rating of 29.3 kW. Its subsystems are schematically shown in figure 4. All experiments were performed during regular serial operation. To provide a real production scenario, the MT has been artificially put in a *Production on Demand*-State which was generated by e.g. stopping the component flow like mentioned in part 2. A time progression of 15, 30, 60, 120 and 180 minutes was used to shut down ancillary units. These durations were estimated by analysis of collected data including real logistic faults. Like mentioned in part 3, the cooling lubricant unit and the exhaust air unit were shut down. After every simulated logistic fault and resulting shutdown of the ancillary units, every part was examinated by an automated rough and contour measurement system. Analyses of PLC data validated the cycle times. Production was immediately possible after every shutdown. Fig. 6 shows the power level during the experiment. The yellow area shows a logistical fault state with shutdown of the mentioned aggregates. Savings about 2kW are achieved.

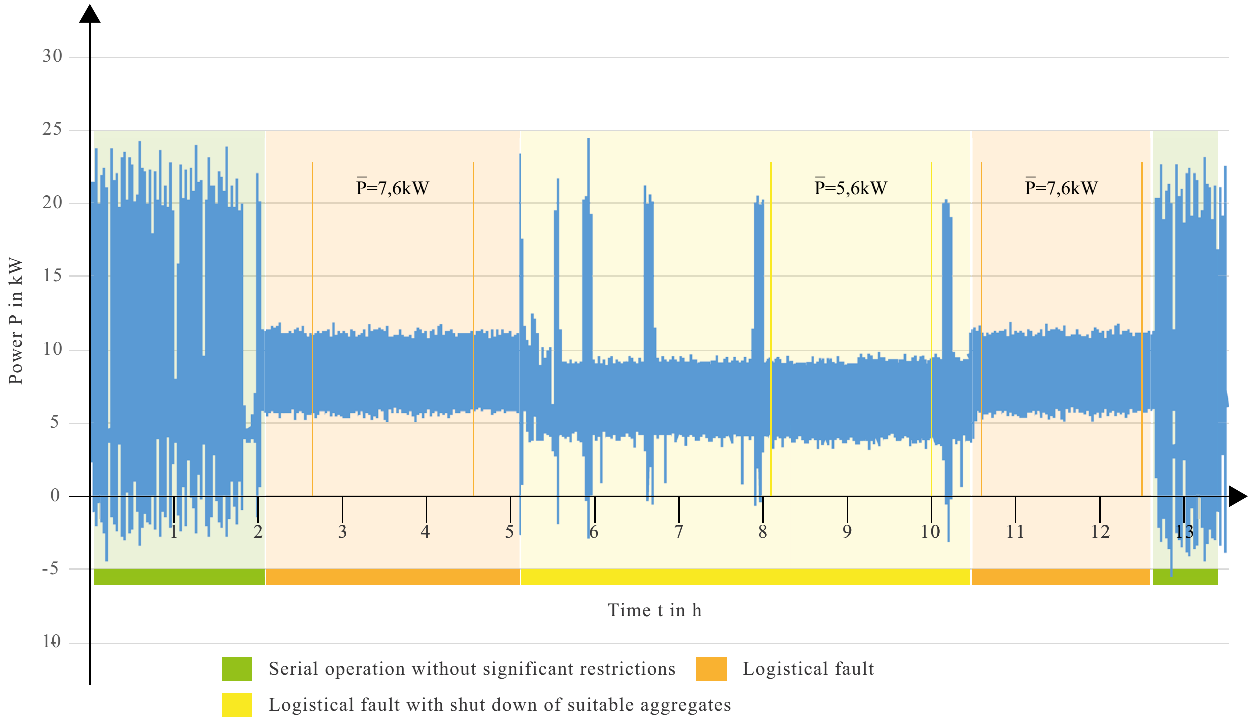

Fig. 6. Consumed Power per MT, utilizing the Standard Energy Manager Algorithm

5. Results and discussion

Switching off two aggregates for four hours reduced the energy consumption by 8 kWh, meeting all requirements. For production-related simulation of shutdowns, different time gradings were created which are intended to represent various failure scenarios experienced in everyday operation. The time sequences were taken from the evaluation, which had been determined in the statistical analysis of the operating states. The decision for the time graduation was made for short and long switch-off periods. This should serve to study the maintenance of process capability. After each shutdown, two to five parts were produced and then examined regarding the required manufacturing tolerances. It was proved in the test series that a shutdown of the coolant pump unit and the exhaust system does not trigger any complications. Consequently, it was decided to conduct a long term experiment over one year. Within this duration, the algorithm did not cause any critical events or issues regarding the product quality.

6. Conclusion & Outlook

The results of the presented experiment with shutdowns of subsystems in non-productive states imply the capability for significant energy optimization. The savings of about 2 kWh were achieved by switching off two units without causing any further complications. In the direct experimental environment, this application was transferred to 100 other identical machines which scales the benefit enormously. The duration of daily logistical irregularities for 100 MTs are about 300 hours in sum or 3h per MT. This will lead to savings about 600 kWh per day. Future work will extend the approach to more ancillary units. However, rolling out such a system to factory level takes much manual effort. New possible parameters of the algorithm could be tapped automatically using machine intelligence, accordingly.

References

[1] IEA, *Key World Energy Statistics 2017*. International Energy Agency, 2017. [Online]. Available: https://www.oecd-ilibrary.org/content/publication/key_energ_stat-2017-en

[2] L. Hu, C. Peng, S. Evans, T. Peng, Y. Liu, R. Tang, and A. Tiwari, "Minimising the machining energy consumption of a machine tool by sequencing the features of a part," *Energy*, vol. 121, pp. 292 – 305, 2017.

[3] H.-S. Yoon, E.-S. Kim, M.-S. Kim, J.-Y. Lee, G.-B. Lee, and S.-H. Ahn, "Towards greener machine tools – a review on energy saving strategies and technologies," *Renewable and Sustainable Energy Reviews*, vol. 48, pp. 870 – 891, 2015.

[4] B. Schlomann, M. Reuter, S. Tariq, K. Wohlfarth, B. Lapillonne, and K. Pollier, *Energy Efficiency Trends and Policies In Industry - An Analysis Based on the ODYSSEE and MURE Databases*. Odyssee-Mure, September 2015.

[5] S. Thiede, G. Posselt, and C. Herrmann, *Industrie 4.0 und die Steigerung der Energieeffizienz in der Produktion*. München: Hanser, 2017, pp. 279–290.

[6] A. Fysikopoulos, D. Anagnostakis, K. Salonitis, and G. Chryssolouris, "An empirical study of the energy consumption in automotive assembly," *Procedia CIRP*, vol. 3, pp. 477–482, 2012.

[7] M. U. Uluer, H. O. Unver, G. Gok, N. Fescioglu-Unver, and S. E. Kilic, "A framework for energy reduction in manufacturing process chains (e-mpc) and a case study from the turkish household appliance industry," *Journal of Cleaner Porduction*, vol. 112, pp. 3342–3360, 2016. [Online]. Available: www.elsevier.com/locate/jclepro

[8] O. Heimann and G. Thiele, "Ganzheitliche Regelung der Energieeffizienz," *Zeitschrift für Wirtschaftlichen Fabrikbetrieb*, vol. 111, no. 11, pp. 710–713, November 2016.

[9] C. J. Bauerdick, M. Helfert, B. Menz, and E. Abele, "A common software framework for energy data based monitoring and controlling for machine power peak reduction and workpiece quality improvements," *Procedia CIRP*, vol. 61, pp. 359–364, 2017.

[10] R. Neugebauer, A. Schubert, B. Reichmann, and M. Dix, "Influence exerted by tool properties on the energy efficiency during drilling and turning operations," *CIRP Journal of Manufacturing Science and Technology*, vol. 4, no. 2, pp. 161 – 169, 2011, energy-Efficient Product and Process Innovations in Production Engineering.

[11] S. Wahren, E. Colangelo, A. Sauer, J. Mandel, and J. Siegert, "Keeping a factory in an energy-optimal state," *Procedia CIRP*, vol. 40, pp. 50 – 55, 2016, 13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use.

[12] P. Eberspächer, "Zustandsmodellbasierte, steuerungsnahe Energieverbrauchsoptimierung von Werkzeugmaschinen," Dissertation, Universität Stuttgart, Stuttgart, 2016.

[13] S. Kreitlein, T. Rackow, and J. Franke, "Energy kpi's, challenges for sustainable manufacturing strategies, analysis of existing rules and indicators in an industrial environment in relation to the establishment of energy benchmark," *Advanced Materials Research*, vol. 1018-1018, pp. 501–508, November 2014.

[14] Y. Oda, Y. Kawamura, and M. Fujishima, "Energy consumption reduction by machining process improvement," *Procedia CIRP*, vol. 4, pp. 120 – 124, 2012, 3rd CIRP Conference on Process Machine Interactions.

[15] A. Verl, "Abschlussbericht for 1088 ecomation: Steuerung des Energiebedarfs in der Fertigung und Steigerung der Energieeffizienz durch Automatisierung," Düsseldorf.

[16] J. Schlechtendahl, P. Eberspächer, S. Schrems, P. Sekler, A. Verl, and E. Abele, "Automated Approach to Exchange Energy Information," in *Future trends in production engineering*, G. Schuh, Ed. Berlin: Springer, 2013, pp. 47–54.

[17] P. Eberspächer and A. Verl, "Realizing energy reduction of machine tools through a control-integrated consumption graph-based optimization method," *Procedia CIRP*, vol. 7, pp. 640–645, 2013.

[18] E. Abele, T. Sielaff, and M. Beck, "Schlussbericht zum projekt maxiem - maximierung der energieeffizienz spanender werkzeugmaschinen," Darmstadt. [Online]. Available: http://tubiblio.ulb.tu-darmstadt.de/64540