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Automatic assessment of machine tool energy efficiency and productivity

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Abstract

This work presents an approach to determine relevant energy efficiency and productivity KPIs of machining processes based on a real-time interpretation of sensor data and machine control data. A comparison of the actual power consumption during machining with an energetic model of the load-free condition enables the calculation of energetic efficiency and primary processing time. The approach was tested on a CNC turning and milling center equipped with power meters and compressed air sensors. Sensor data as well as relevant machine control data are read, processed and recorded via SCADA software in order to automatically calculate certain KPIs.

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Keywords: Machine tool; Monitoring; Sensor; Machine control; Data acquisition; Modelling; Energy efficiency; Productivity; OEE

1. Introduction and motivation

As manufacturing industries are facing economic challenges due to increasing global competition, they continually need to increase productivity while reducing manufacturing costs. The industrial sector is a substantial consumer of energy and other resources and thus causes severe environmental impact [1-3]. Therefore, ambitions to reduce the energy intensity of manufactured products are suitable to enhance both economic competitiveness and environmental sustainability.

In recent years, different legislative and normative measures have been taken in order to reduce industrial energy consumption. ISO 50001, for instance, provides a systematic approach to continuously improve energy performance and specifies requirements for process and equipment design, measurement and documentation [4]. EN 16231, on the other hand, suggests a methodology for the evaluation of energy data in order to determine the energy efficiency of certain units (such as production systems) enabling energy performance monitoring and a comparison with other units [5]. Energy efficiency benchmarking is a suitable way to reveal optimization potentials concerning energy consumption.

Utilized in great quantities, machine tools constitute substantial industrial energy consumers [6, 7]. Therefore, a reduction of machine tool energy demand can significantly improve the environmental performance of manufacturing processes and thus the CO_2 footprint of consumer products.

A traditional product lifecycle consists of three stages: manufacturing, use and end of life. For a machine tool itself, the use phase is the most energy intensive phase causing 60% to 90% of CO_2 emissions during its lifecycle [8].

Recently, a draft standard for the environmental evaluation of machine tools during their use phase was introduced, presenting a methodology for a reproducible quantification of energy supplied to the machine in different operating conditions [9]. Gontarz et al. presented a modular configuration approach for machine tools based on multichannel measurements in order to improve energy efficiency and enable total cost of ownership (TCO) calculations [10].

Several studies have been carried out in order to model the energy consumption of machine tools and thus to determine the environmental impact of goods produced [11-16].

The machining time is a key influence factor for the energy demand of machine tools, especially such with high base load (i.e. machines with large peripherals such as hydraulic, machine cooling, exhaust and cooling lubricant systems).

Various studies have shown that high material removal rates decrease machine tool overall energy consumption when keeping the volume of removed material constant due to decreasing machining time [13, 17, 18].

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Further optimization potential arises from a proper choice of the tool path strategy during machining [12, 18, 19].

As a conclusion, it is of high importance to use optimal machining procedures and parameters in combination with performant tooling systems in order to minimize cycle times and thus energy consumption. However, over the course of machining, the process performance might change due to tool wear, suboptimal machine settings or operating errors. Hence, it is expedient to monitor certain performance indicators over time in order to assess and compare different processes.

A typical energy performance indicator (EnPI) used for benchmarking within or between units is the specific energy consumption (such as energy per unit produced) [5]. Emerging trends in such indicators can not only help to validate changes in energy efficiency but also act as evidence for issues like process plan deviations and changes in process stability or quality.

Progress in the field of sensor and data acquisition technologies enables real-time acquisition and interpretation of machine tool data. Vijayaraghavan et al. developed an automated machine tool energy monitoring system using MTConnect and applied event stream processing techniques to automate the analysis of energy consumption [20]. Hu et al. introduced an on-line approach for energy efficiency monitoring of machine tools via spindle power measurement based on power balance calculations [21].

Shin et al. presented a predictive analytics model for machining processes using neural networks [22]. In their work, big data infrastructure was fed with STEP-NC plan data and MTConnect machine monitoring data to derive an analytic model for the machine tool power consumption depending on cutting parameters.

Bhinge et al. also introduced a machine monitoring system architecture based on data acquisition via MTConnect [23]. A data-driven energy prediction model using Gaussian process regression was developed using power consumption sensor data as well as operating data obtained from NC-code and cutting simulation.

Eberspächer et al. presented a model and signal-based power consumption monitoring concept and approaches to reduce the power consumption [24]. In their work, machine control data read via OPC UA and additional sensor data are used as input for consumption simulation models to provide the machine operator with detailed power consumption and distribution data.

This work presents a different machine monitoring approach and a methodology to determine relevant energy efficiency and productivity key performance indicators (KPIs) of machining processes based on real-time interpretation of sensor data and machine control data. A comparison of the actual power consumption during machining with an energetic model of the load-free condition enables the calculation of the energetic process efficiency and the primary processing time. The approach was tested on a CNC turning and milling center equipped with power meters and compressed air sensors. Sensor data as well as relevant machine control data are read, processed and recorded via SCADA software and certain KPIs are automatically calculated, visualized and stored.

2. Experimental setup

In the framework of the research project “eco2production”, which focused on the development of methods and tools to enhance energy efficiency and productivity of producing SMEs [25], an energy monitoring and control system was implemented in a pilot factory equipped with machine tools. The electric power and compressed air consumption of these machines and certain sub-components as well as peripherals is recorded and visualized. Furthermore, machine control data acquisition was implemented for one of the machine tools. The used SCADA software system, SIMATIC WinCC Open Architecture, supports different communication protocols and features a SQL-based database.

Fig. 1 shows a diagram of the experimental setup for sensor and machine control data acquisition for the CNC turning center EMCO MAXXTURN 45. The machine tool features a movable counter spindle as well as a tool turret with driven tools (for milling and drilling operations) and thus seven individual drives. The machine has a power rating of 25 kVA and main spindle and counter spindle drive capacities of 13 and 10 kW, respectively.

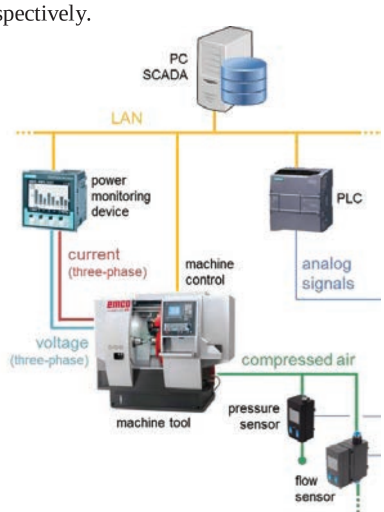

Figure 1. Diagram of the experimental setup.

Active power is internally calculated by SENTRON PAC 4200 power monitoring devices from measured electric voltage and current signals. The according data are transferred to the SCADA system via MODBUS TCP protocol.

Compressed air volumetric flow and pressure are measured with FESTO SFAB and SDE1 sensors, respectively. The sensor data are read by SIMATIC S7-1200 PLC and transferred to the SCADA system using TCP/IP based S7 messaging. The same S7 protocol is used to read drive data (such as active power consumption and speed) from the SINUMERIK 840D sl machine control via according data block addresses.

For both communication protocols (MODBUS TCP and S7), data transmission is software-driven with polling cycles of 100 ms. The realized temporal resolution of signals read from the machine control and PLC is around 100 ms on average. The power monitoring devices, however, deliver new data in a mean interval of around 200 ms.