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Resource Consumption Monitoring in Manufacturing Environments

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Abstract

Resource consumption measurement, analysis, and improvement in the context of sustainability in manufacturing reveal extensive fields of research and have become important in order to fulfil multiple requirements in ecological, economic and legislative activities. Solutions for energy consumption measurement in manufacturing are known but rarely implemented due to several reasons such as high costs, implementation complexity or unknown information. Despite the availability of several standards and guidelines towards environmental performance evaluation and optimization as well as punctual energy measurements for production systems, a user-oriented monitoring system to gather the relevant data in an efficient way has not been formulated yet.

The following paper introduces a condign monitoring strategy and architecture that fills this gap and fulfils the requirements of accuracy within an acceptable cost-to-information ratio. A combination of internal sensors, external sensors and simulation provides comprehensive information of the monitored manufacturing system according to ISO 14955 and ISO 50001 standards. The implementation is verified within an industrial case study and meets the industrial needs in line with the current legislation. Further, the revealed information enables users to apply micro and macro-optimization activities.

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Keywords: Energy consumption, machine tool measurement, energy efficiency in manufacturing, optimization.

1. Introduction

The manufacturing industry has a strong motivation for the evaluation and implementation of energy efficiency measures in production. This motivation is not only given by the legislative pressure, arising from the European directives 2009/125/EC [1] and 2012/27/EU [2], but is also strongly economically driven with beneficial effects on the environment. The standards ISO 50001 [3] and ISO14955 [4] introduce energy management systems and measurement procedures for the manufacturing sector. Up to now, more than 1000 companies received the ISO 50001 certification [5], which is also mandatory for partial tax exemption. The industrial sector contributes to one third of the worldwide electricity consumption. Thus, this sector reveals a major leverage for the reduction of CO_2 emission, as pointed out by Mandil [6].

A fundamental base and a first step for the optimization of machine tools and production systems towards an increased energy and resource efficiency is seen in the appropriate and detailed data acquisition on installed machine tools and production systems. Already by the use of monitoring systems, optimizations up to 30% are possible through awareness raising and adequate code of practice as shown by Sextl [7] for the automotive industry. The revealed information is further essential to perform a detailed and accurate data analysis for the implementation of improvement and optimization measures. In the context of the factories of the future and industry 4.0, it is essential to have data acquisition capabilities providing the right information at the right time to indicate adequate actions for improvement. Currently this information is only partially given as a detailed resource consumption data acquisition can be complex and costly. The IEA [8] as well as the European Commission [9]

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estimate an energy saving and energy efficiency potential in the manufacturing sector between 13% and 29%.
In the case of manufacturing systems these saving potentials can only be achieved by system optimization and specific improvements, through PDCA cycles, rather than by rule-based decisions, such as general avoidance of compressed air. In this respect, assessing energy efficiency performance in production has become a major challenge and a strategic goal for manufacturing companies. This can only be achieved by proper data acquisition on the energy and resource consumption of machine tools and production systems.

Nomenclature

A_o	Weighting factor for power consumption behaviour
ANR	Standard atmospheric state
CNC	Computer Numerical Control
EDM	Electrical Discharge Machining
ERP	Enterprise Resource Planning
I/O	Input / Output
KPI	Key performance indicator
OPC	OLE for process control
PDCA	Plan do check act cycle
PLC	Programmable logic controller
TCP	Tool center point

1.1. Objective

Assessing the power consumption and the energetic behavior of machine tool components, based on direct measurements with a high time resolution, are considered as expensive due to complex system architecture and required sensor implementation. Resulting benefits of this detailed evaluation is the quantification of the improvement potential and the indication for possible analysis applications. As shown by Vijayaraghavanan and Dornfeld [10] the indication of possible analysis and measurement methods are unknown in most cases or the implementation is too laborious for the expected outcome. Furthermore, the combination with different resources and energy forms can cause complex, expensive and unstable sensor architectures. For this reason most monitoring applications of today focus on the tool wear or on the machine tool condition monitoring [11]. It is therefore obvious, that energy and resource monitoring systems are confronted with the tradeoff between reliability, accuracy and costs. The following monitoring strategy, as a new patented approach, is paving the road for smart monitoring devices by keeping implementation costs low, whilst ensuring a high level of detail in the revealed information. To do so, an implementation method leading to a customized monitoring architecture, based on different information sources, is created. The results are implemented within an industrial use case on two different machine tools to ensure the interoperability for different machine tool controls and machining processes.

1.2. Implementation environment

The following research is embedded in the FP7 project FoFdation as described by Larreina et al. [12]. The FoFdation project enables optimization and decision making in order to produce the first part right while evaluating all required information before, during, and after the machining process. For this reason a reliable monitoring system on the machine tool level must be present. The following results are developed and implemented on two machine tool systems at the Centro Richerche FIAT (CRF) and AgieCharmilles (GFAC).

1.3. Theoretical requirements

Monitoring is commonly defined as continues data acquisition for supervising activities in order to ensure the required performance targets. Data capturing for monitoring applications can either be done by the use of sensors or precise simulation. As the machine tool is understood as an assemblage of different machine tool components, it is mandatory to capture all relevant energy flows, such as electrical consumers, compressed air and material flows of each machine tool component, as introduced in ISO14955 [4]. Simulation can provide all different kind of information. For monitoring purposes, based on the achievable accuracy and number of required input parameters, models are only partially applicable. A major requirement is the modularity as confirmed by Verl et al. [13]. This is required to serve the variety given by various machining procedures as well as the individual machine tool and production system architecture and configuration. As optimization potentials can vary from 10% to 50% an accuracy of +/- 10% is mandatory for monitoring applications. Previous research on measuring equipment and measurement methods in the context of the ISO14955 [4] revealed that a detailed machine tool measurement can only be made when measurements are performed on the component level. Furthermore the energetic behavior is mostly represented by the auxiliary equipment. A basis for this application is provided by the multichannel measurement approach [20]. By the multichannel measurement approach, including compressed air flow and fluid flow measurement, an overall accuracy of +/- 5% can be reached. For this reason the accuracy of models have to be in the range of +/- 5% to 10% in comparison to the sensor accuracy for monitoring applications. A survey among machine tool users [36] revealed that customers are unwilling to invest more than 10% of total machine tool system costs for a monitoring system. For this investment it is requested that monitoring activities are able to evaluate and approve defined goals of an organization. A main requirement of the applied monitoring system is to perform macro-optimization, e.g. production scheduling or automated machine tool switch off, and macro-optimization, e.g. machine component control. Dietmair et al. [22] constitutes micro-optimization based on the revealed information to set or force machine components to a defined energetic state. The interrelation between micro- and macro optimization is also shown by Verl et al. [13] where the information can be used for different aspects, e.g.

analytic, learning, planning and control models. Substantial improvement potential is seen in the dynamic component compensation and control according to the current machining process. For this reason monitoring systems are required to provide all relevant information on a real-time basis with possible interfaces to further systems such as Manufacturing Execution Systems (MES).

The application of energy and resource monitoring to enable energy efficiency methods must be given without compromising the flexibility, quality and output of the manufacturing system. Therefore, main attention is given to auxiliaries and non value add machine tool states with limited influence on the machining process.

2. State of the Art

Monitoring systems on machine tools are mainly used for the surveillance of the machining process, tool breakage detection, TPC position verification, vibration analysis, and thermal state surveillance as introduced by Tönshoff et al. [14] and Byrne et al. [11]. Vijayaraghavana and Dornfeld [15] introduced an energy machine tool monitoring approach based on event stream processing, using the standard interface MTconnect. A similar approach is given by the Profienergy working group [16] with the limiting factor that only devices can be monitored and controlled that are equipped with a standard data bus, e.g. MTconnect, Profibus, Profinet, AutomationML, OPC or IO-Link. Behrendt et al. [17] introduced a monitoring approach based on a three-steps methodology and aggregated system level. A model based energy monitoring approach is introduced by Hu et al. [18]. This approach mainly focuses on cost saving through indirect data capturing methods without using external sensors but is based on empirical data. This approach covers only the main spindle and depends on the cutting parameters which have to be revealed through extensive cutting experiments. Verl et al. [13] focus on direct machine tool control mechanisms through simulation of components. Besides a different intended application and expected inaccuracy, these approaches are not considered for monitoring applications. O´Driscoll et al. [19] introduced a metering approach on the factory level. This can be used to calculate values for the manufacturing performance and KPI evaluation. However information on the component level cannot be revealed or require additional sensors. For this reason the improvement potential on the machine tool component level cannot be tackled.

The reviewed approaches show direct and indirect data capturing methods based on measurements or simulations. The following introduced approach combines direct and indirect sources and available data from the machine tool control. This results in the capturing of the full energetic picture of the machine tool including the auxiliaries, different energy forms, and machine tool modes.

3. Methodology

The following methodological approach leads to the implementation of a comprehensive energy and resource monitoring system. This approach is based on the following three implementation steps:

- System measurement and analysis based on the multichannel measurement.
- Subcomponent analysis and for system architecture definition.
- Implementation and verification based on results from multichannel measurement.

3.1 Component classification

As machine tools are highly individual in their configuration, machining process, functionalities and use, the following approach describes an implementation method which results into a customized energy and resource monitoring architecture. In line with the commonly accepted energy breakdown by Dahmus and Gutowski [23]; idle, run-time, and production mode, the following approach classifies the energetic behavior of machine tool components in three different consumption behavior modes. These modes are:

Constant: Constant machine tool components are represented by a process independent energetic behavior and are mostly used to maintain a certain machine tool state, for example maintaining the thermal state. Those components are either on or off and show a fixed power level within the measurement accuracy of +/- 5%. In the given methodology, constant components are classified by their time on level calculation and $\boldsymbol{A}_{\mathbf{O}}$ [-] value accordingly to Gontarz et al. [24]. $\boldsymbol{A}_{\mathbf{O}}$ [-] is a weighting factor which indicates the mode of operation of the component, whereas $\boldsymbol{A}_{\mathrm{O}} \geq 0.9$ indicates a constant energetic behaviour.

Controlled constant: Controlled constant components, e.g. pumps or chip conveyor are represented by a periodic switch on and switch off mode which is controlled by the PLC or external devices. In most cases the PLC status indicates the current ON/OFF status of this component. The energetic behaviour during operation mode can be separated into three phases that have to be either measured or simulated. Those phases imply the start-up and switch-off peak which need to be recorded with a minimum resolution of 5Hz, to ensure the evaluation of the peak amplitude and length and the constant phase as defined above. Components in this category are represented by an $\boldsymbol{A}_{\mathbf{O}}$ value of $\boldsymbol{A}_{\mathbf{O}}$ [-]≈ 0.5.

Variable: Variable components, e.g. spindle or axis, are represented by a process dependent and heterogeneous energetic behaviour. In monitoring applications those components need to be measured with a minimum resolution of 5Hz or are required to be simulated with a precise model. This can either be done by the evaluation of given forces at the TCP or parameter readout of the EDM generator to achieve an accuracy of at least +/- 5%. The behaviour of these components is characterized by the weighting factor $\boldsymbol{A}_{\mathbf{O}}$ [-]< 0.5.

Other energy flows, such as compressed air are also considered are classified according to the component characterization as introduced above. The presented monitoring approach includes the measurement or simulation of media flows and calculates the measured values into electrical equivalent, e.g. standard cubic meter per hour (m^3/h (ANR)) into kilowatts (kW). This can be done by either using a general benchmark factor, e.g. 0.13 kW/m^3 for compressed air according to [25] or individually measured with the following equation ((1).

$$C_{cair} = \frac{\sum_j W_{el,j} + \sum_i C_{th,i}\left(Q_{th,i}\right)}{V_n} \qquad (1)$$

This formula reveals the individual transformation factor C_{air} and combines the electrical energy consuming components (power of the compressor W_{el}) with additional compressor functions $C_{th,i}(Q_{th,i})$, for example fluid cooling, as a function of the consumed compressed air V_n at normal conditions. Therefore this approach includes a defined conversion rate into an electrical equivalent from flow (m^3/h (ANR)) to power (kW) in two ways.

3.2 Monitoring system architecture

In the following the information sources are selected accordingly to the introduced machine tool component classification from paragraph 3.1. One of the main problems encountered by commercially available effective power sensors and power analyzers besides the accuracy and resolution is the amount of available measurement points. A five axis milling machine tool requires 15 to 20 measurement points for a detailed measurement. This requirement can lead to a high implementation effort and costs. For cost saving reason without compromising data accuracy including the variety, the type and energetic behavior of each component, the following methodological approach is chosen.

Internal sensors

According to the requirements related to cost saving, accuracy, and reliability all available internal sensors within the machine tool control are used in the following approach. Open computer numerical controls (CNC), as developed within the FoFdation project, facilitate users to use various programming languages, operating systems, control strategies, system dynamic models and sensor signal processing. The required power information is available from the drive controller as part of the drive control loop and internal reference parameter on a system variable, e.g. *AA_Power* at SIEMENS 840D controls. Altintas and Erol [26] are using a similar procedure in order to access the motion and machining process control. This allows accessing the power consumption information on control-dependent and highly variable machine tool components, such as spindles, axis, or generators, without using external sensors.

External sensors

External sensor are required for variable machine tool components (A_O *[-]< 0.5)* and where simulation results fail to reach the the required accuracy of +/- 5%. External sensors are needed for internal calibration and verification in combination with the PLC controlled simulation and internal sensors. For this reason at least one external sensor has to be installed on the main power supply of the machine tool. The amount of needed sensors can be further minimized by relevance of the measurement component as defined in ISO14955 [4] or suitable master-slave and control logic, for example on cabinet cooling or cooling fans. Table 1 shows the used external sensor for the applied energy and resource monitoring system architecture.

Table 1. Possible application of sensors

Sensor type	Energy form	Communication
Christ CLT 310	Electric	RS232 / analog
Accuvim II	Electric	RS485/Modbus
Sentron PAC4200	Electric	Modbus / Profibus
Postberg&Co BS	Air flow	RS232 / analog
VP FlowMate	Air flow	RS485 / Modbus
EndressHauser	Fluids	RS485 / Modbus

Simulation

Most machine tool components represent either a constant or controlled-constant energetic behavior. For those components a virtual measurement channel, based on PLC controlled I/O model can be defined. In order to achieve the highest accuracy either a detailed component measurement or a physical model can be applied. In both ways three different component states have to be distinguished; start-up phase, constant phase, and switch off phase, leading to the exact energetic behavior and power level. The model inputs are received by the PLC status and indicate the machine component state, such as on, off or standby. This information in combination with the recorded component power measurement or precise component model reveals the detailed energetic behavior of the machine component without the use of any external sensor. To ensure the accuracy of the monitoring system and for the internal calibration the sum of all simulated components (ΣP_{sim}) is compared continuously with the external sensor at the overall machine tool supply (P_{ex})((3). In the case of a deviation of +/- 10% the virtual measurement channel must be recalibrated or the energetic behavior of the simulated component changed. For instance in the case of a component breakdown.

$$\Delta P_{test,n} = P_{ex} - \sum P_{sim} \qquad (3)$$

$$\text{with} \quad 0.9 \times \Delta P_{test,1} \leq \Delta P_{test,n} \leq 1.1 \times \Delta P_{test,1} \qquad (2)$$

3.3 Implementation of the monitoring system

For the implementation of the energy and resource monitoring on a random machine tool system a detailed multichannel measurement is required to evaluate the energetic behavior and interdependencies of all active machine tool components based on the machining process and machine tool states. Based on those measurements the type and quantity of required data sources can be evaluated and the parameterization of the simulation models and virtual channel can be done. In combination the energy and resource monitoring architecture is shown in Fig. 1.

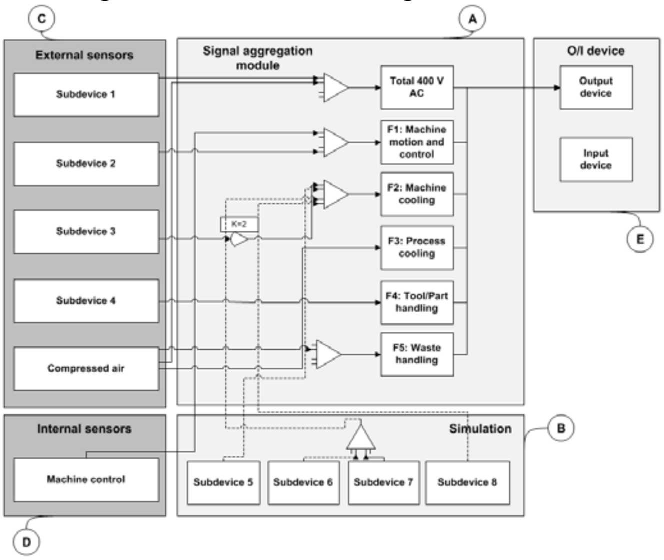

Fig. 1. Overall architecture of the energy and resource monitoring system (EMon).

A: Module A represents the signal aggregation module. Consumer signals are synchronized to a time equidistant format with a resolution of 5Hz with a polynomial interpolation algorithm.
B: Module B represents the simulation block which contains all consumers that can be simulated. This module is part of the signal aggregation module with a communication interface to the PLC.
C: Module C represents external sensors for effective power consumption, e.g. smart meter and compressed air flow measurement equipment as shown in table 1.
D: Module D represents the machine tool numeric control (NC). Consumer signals from the control must be available, e.g. by synchronous actions or other readout options.

4. Case study

Two case studies were carried out for the system implementation. For the proof of concept one of the two case studies is introduced in this paper. The monitoring system was implemented on the EDM machine tool CUT200 by AgieCharmilles. Accordingly to performed pre-measure-ments (figure 2), the energetic behavior of EDM machines is dominated by the generator power and auxiliary pumps. The generator power can be revealed by the machine tool control, whereas the auxiliary pumps represent constant components. Therefore the monitoring architecture requires only a minimal

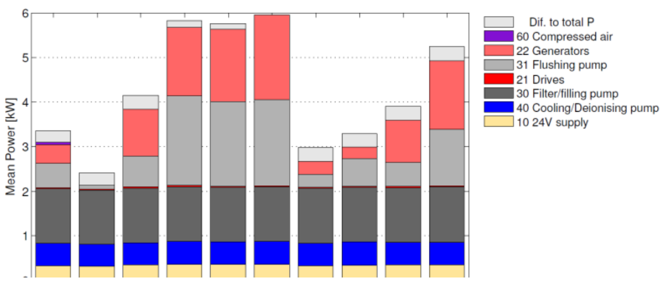

Fig. 2. Multichannel measurement on the CUT200 machine tool in different machine tool modes and machining processes.

number of external sensors.

Figure 2 shows the average power consumption of the machine tool components in different machine tool modes. The measurements M01 to M08 represent different machining processes of the CUT200 machine tool with various process parameters such as wire thickness and generator power. Based on this analysis and the $\boldsymbol{A_O}$ value calculation, the variance of the machine tool component can be quantified. This results in a process-independent and predictable energetic behaviour of the cooling and dimensioning pump, the 24V power supply and the filter and filling pump. For this reason those components are selected for simulation. The input parameters for those components are given by the individual PLC status from each machine tool mode. Further the measurements show that the drives and the compressed air have minor influence on the power consumption, whereas the generator and the flushing pump are strongly variable and highly process dependent. For this reason the flushing pump and the generator must be measured in order to provide a suitable and adequate monitoring functionality. The application of the resource and monitoring approach for this machine tool requires therefore the application of three external sensors to provide the entire energetic behaviour of the machine tool components. The revealed synchronized machine tool component information can now be further used of any other macro and micro optimization features.

Discussion and Outlook

The introduced case study with the implementation of a monitoring strategy proofs that detailed and required information and the energetic behavior of machine tools can be revealed and used to indicate optimization on the component level and through component control. The approach further shows a universal monitoring system with a reasonable cost to benefit ratio. Thus, detailed information on the component level can be collected and further aggregated for the capturing of production data, e.g. MES or ERP systems. Furthermore, the case study proofs that the modular software and hardware architecture enables a suitable monitoring approach for different applications and machine tool types.

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