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Resource consumption measurement in manufacturing environments

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Abstract

Efficient resource consumption and sustainable manufacturing reveal an extensive field of research and have become increasingly important in fulfilling multiple requirements in ecological, economic and legislative activities. The energy consumption in manufacturing and shop floor level is still not well understood or is based on assumptions. In order to support optimization activities, measurement and monitoring strategies have to be developed that deliver the desired accuracy within an acceptable cost-to-information ratio.

This paper introduces a condign strategy for manufacturing monitoring which merges Environmental Value Stream Mapping (EVSM), a method which originates from lean manufacturing, with power consumption measurement techniques, required accuracy and measuring point definition, elements adapted from machine tool measurements. The applicability is verified in a use case and meets the industrial needs in line with current legislation and desired accuracy.

From the combined product- and manufacturing process viewpoint, this paper addresses the trade-off between strategic goals of an organization regarding required information and accuracy of information obtained from energy consumption measurements on the shop floor.

Keywords:
Energy efficient manufacturing, energy consumption, monitoring, process chain

1 INTRODUCTION

The manufacturing sector is confronted with major challenges and requirements, such as productivity, flexibility, product variability and environmental constraints. The constraints which are transferred into company strategies require adequate measurement and monitoring procedures on the initial point of manufacturing – the shop floor level.

According to the International Energy Agency (IEA [1]), the manufacturing sector is one of the major consumers of energy and emitters of CO₂. The IEA [2] as well as the European Commission [3] estimate an energy saving and energy efficiency potential in the manufacturing sector between 13% and 29%.

In the case of complex manufacturing systems these saving potentials can only be achieved by continuous and specific improvements much more than by rule-based decisions. In this respect, assessing energy efficiency performance in production has become a major challenge and strategic goal for manufacturing companies.

Bunse et al. [4] conclude that various energy efficiency performance measurements already exist on an aggregated sector, but that these performance measurements remain deficient in assessing the energy efficiency performance of single manufacturing processes. In addition, the manufacturing industry has expressed the lack of appropriate energy efficiency metrics on the machine, process and plant level as well as missing benchmarks which pertained to energy efficiency and energy-profiles on machines and equipment [5]. Hesselbach et al. [6] underline the consolidated economic motivation for optimization procedures by saving energy in manufacturing.

The awareness of energy use on the shop-floor level and the integration of energy efficiency performance monitoring systems in production management are essential to foster the implementation of energy efficiency improvements.

This paper focuses on the data acquisition of energy consumption, the type and manner to support Eco-Efficiency Performance Measurements in manufacturing systems. Units of primary interest are machine tools, representing a major part of the equipment found on shop-floor level.

2 RELATED WORK

Relevant elements of the environmental performance measurement and monitoring are addressed and discussed in the following sections.

2.1 Performance Measurement and Monitoring

Dickinson et al. [7] describe stakeholders as the ‘final judge’ of organizational performance. Subsequently, efforts to increase performance need to be aligned with as well as measured against stakeholder requirements. Using this channel, customer demand for environmentally friendly processes, legislative pressure and resource scarcity has caused an increasing organizational awareness for environmental performance [8, 9]. Strategic environmental goals have been formulated and manifested in Corporate Responsibility Reports (CRR) [10]. To contribute to these goals on the shop-floor level, production managers need to exploit the existing potential for improvements in the domain of Production Planning and Control (PPC) and machine
economic performance. In contrast to traditional value stream
scrap rates and lot sizes) to measure the corresponding
storage) and in all relevant data (cycle times, setup times,
indicators (EnPIs), or more general Key Performance
elements for the control mechanism are energy performance
philosophy of DIN EN ISO 9001 organization principles. Key
EnMS described in DIN EN ISO 14001 and is in line with the
it represents an integrative element of the environmental
design of an energy management system (EnMS); moreover,
input/output process model.

The EVSM methodology (Figure 3) as described above
represented by subsystems (L3).

The standardization approach ISO 50001 [15] suggests the
design of an energy management system (EnMS); moreover,
it represents an integrative element of the environmental
EnMS described in DIN EN ISO 14001 and is in line with the
philosophy of DIN EN ISO 9001 organization principles. Key
elements for the control mechanism are energy performance
indicators (EnPIs), or more general Key Performance
Indicators (KPI) for industrial improvement, which are
currently being elaborated by the ISO22400-2 [16].

The EVSM methodology (Figure 3) as described above
predefines measurement points on the manufacturing level
(L1) with their aggregated energy in- and output(s) are
given as Purchasing (P), Logistics (L), Manufacturing (M),
Sales (S) and Distribution (D). Manufacturing could be
subdivided further into different manufacturing processes
(L2), e.g. milling or grinding. In more detail some processes
can be performed by one or more machine tools and are
represented by subsystems (L3).

The need for a measurement approach as described in this
paper is coupled with revealed requirements from both macro
optimization with aggregated requirements and micro-
optimization with a process-oriented approach in order to foster
energy efficiency in manufacturing and the shop floor.

For instance, the reduction of machines’ idle times as a
means of avoiding unnecessary energy use in non-value add
machine modes represents macro-process optimization.
According to [17, 18], a macro process optimization further
selects the optimal sequence of multiple manufacturing
processing steps within production. Kirschen [19] and
Newman et al. [20] present various optimization activities and
strategies on the macro level.

Herrmann et al. [21] provide a systematic evaluation
approach in five steps to foster energy efficiency by
considering process chains, the efficiency of production
equipment and the interaction with technical building services
(TBS); this is done to establish significant load profiles and to
enable an integrated simulation.

2.2 Procedure and Application Level

As a combination of different production processes, a
production system comprises multiple application levels for
measurement and monitoring systems. A distinction is also
seen in the intended information for monitoring, direct
optimization or comparison toward similar entities. Possible
process-independent application levels introduced by
Vijayaraghavana and Domfeld et al. [22] are the
Manufacturing Supply Chain, Manufacturing Enterprise,
Manufacturing Equipment, Subcomponent and Tool Chip
Interfaces. Weck et al. [23] subdivide process-dependent
Manufacturing Equipment further according to its degree of
automation.

Depending on the individual measurement and monitoring
target, the application levels can be subdivided generally as
follows:

Figure 2 illustrates potential application levels that can be
considered as black box models with defined energy in- and
output(s). For instance, application entities on the Enterprise
Level (L1) with their aggregated energy in- and output(s) are
given as Purchasing (P), Logistics (L), Manufacturing (M),
Sales (S) and Distribution (D). Manufacturing could be
subdivided further into different manufacturing processes
(L2), e.g. milling or grinding. In more detail some processes
can be performed by one or more machine tools and are
represented by subsystems (L3).

The EVSM methodology (Figure 3) as described above
predefines measurement points on the manufacturing level
(L2) since this application level represents a good relation
between strategic management and manufacturing. It also
enables the association of macro- and micro optimization possibilities. The selected measurement spot and its corresponding system boundaries have to fit the target evaluation of a company. Depending on the Technical Building System (TBS) and infrastructure, the infeed of energy can be ramified to the utmost degree which makes sensor implementation difficult or even impossible.

Figure 3: EVSM according to Sproedt / Plehn [14].

Summarizing the state of the art, the authors structure the procedure in four steps that can be identified as a generic procedure for the design of monitoring systems as follows:

I System description: An overview and analysis of the manufacturing system, its system boundaries and related energy forms according to individual goals.

II Focusing / Definition: The identification of energy relevant entities of the system, e.g. key manufacturing processes or machine tools.

III Technical analysis: An analysis and pre-measurement of relevant entities as well as an understanding of the systems’ sub-functionalities.

IV Implementation of monitoring: Technical design and implementation, data acquisition, data aggregation and transmission to manufacturing execution systems (MES), simulations or other systems.

2.3 System boundaries
The measurements at this aggregated level not only reflect the actual energy consumption of the machines’ target activity, e.g. chip formation, but include the auxiliaries supporting the target activity and possibly different energy forms as well. Auxiliary functions can have a major influence on the energy consumption in various machine modes according to Dahmus and Gutowski [24]. To foster relevant consumption on defined system levels the system boundary for the measurement application needs to be particularly defined. The micro optimization is characterized by specific operations and parameters necessary to create a feature within a manufacturing process [18]; in addition, all relevant (sub-) components have to be taken into account. Standard communication interfaces which are used between the numeric control (NC) and PLC with Manufacturing Execution Systems (MES) for monitoring purposes, e.g. Profibus or OPC, neglect information from (sub-)components in most cases and represent a constricted system boundary.

Figure 4: System boundary for machine tools, according to ISO/DIS 14955-1.

ISO 50001 postulates the system boundary covering all energy-relevant areas and represents an aggregated approach. ISO/DIS 14955 draft standard [25] defines the measurement system boundary of a manufacturing system as the asset of all necessary consumers that influence the output and quality of the produced product (Figure 4).

Either definition implies the inclusion of different and individual energy forms, e.g. electric power, compressed air and eventually other supplies.

2.4 Energy Forms
Forms of useful energy, in accordance with the VDI 4608 definition [26], in manufacturing are commonly electricity and compressed air. Other media and energy forms, e.g. steam and cooling water, must be considered if they are relevant according to ISO 50001 [15] and the individual monitoring target. As stated in the EUP-Report by Fraunhofer IZM [27], power consumption has the highest relevance of environmental parameters in comparison to others. The same applies for not only the energy input but the output and the material used according as well. In most cases the output energy is waste heat; current measurement procedures are either uncertain or too complex and are further neglected in the energy accounting.

Provided measurements revealed that machine tools can be distinguished into three distinct classes:

Class 1: Single feed input, e.g. electrical power only.

Class 2: Multi feed input, (i.e. a) combination of multiple inputs in addition to different resources.

Class 3: Machine tool with dependent environmental infrastructure, such as cooling or conditioning.

For Class 1 and Class 2 machine tools power supplied can be measured at the entry point of the system boundary and integrated over time:

$$\sum E_{\text{eff}} = \int P_1(t) + \ldots + \int P_n(t)$$  \hspace{1cm} (1)

When measuring different resources, transformation factors must be provided in order to have the ability of aggregating different resources within one overview.

2.5 Technical analysis and measurement equipment
In order to define appropriate measurement and monitor goals it is essential to understand the basic energetic behavior of manufacturing systems. For instance, the identification of process-dependent (variable) and process-
independent (constant) energy consumption on the machining system is crucial for further analysis on aggregated levels. Devoldere et al. [28] state that about half of the machine tool energy consumed during the use phase, especially in single part manufacturing, is consumed when the machine is not in actual production mode but in various kinds of operation, e.g. standby, modes. The statement can be confirmed by looking at power measurement series of machine tools, for example by Vijayaraghavan et al. [22]. Additional information on the current machine state, e.g. on, off, process, as well as manufacturing data such as produced part, supports further analysis on the machine tool.

Measurements at an aggregated system level neglect information on the component level, resulting in the statement, that the periodic energetic behavior of a manufacturing system is product related, process related, component dependent or a combination of all three possibilities. As stated in chapter 2.4 various energy forms have to be considered and aggregated, e.g. compressed air flow into effective power. This requires a profound knowledge of the assessed energy form and its enthalpy as well as related conversion losses. An analysis of all relevant entities and the understanding of the systems' sub-functionalities are therefore crucial in order to operate on aggregate levels.

2.6 Measurement Equipment

State of the art measuring equipment for energy measurements in manufacturing is mostly focused on measuring effective electrical power $P_{\text{eff}}(t)$. O’Driscoll et al. [30] assess different metering systems which reveal different options in the data output and system configurations based on a flexible monitoring system. Behrendt et al. [31] and Avram et al. [32] use conventional single channel 3-phase metering systems in their measurement activities. The requirement for the measurement equipment within manufacturing is strongly dependent on the intended application. In most cases a 3-phase system for voltages up to 600V and currents up to 100A is required. An output of 1 Hz with a pre-sampling of 12.5 kHz, as used by (Behrendt), fulfills the Shannon theorem by far but is not sufficient enough to assess fast dynamics on a machine tool [33].

To visualize and analyze fast dynamics on machine tool systems, e.g. spindle start up or tool change, output rates of at least 5 Hz must be guaranteed [34]. For monitoring purposes and considering an aggregated application level as stated in chapter 2.2, output rates of 1Hz are deemed sufficient.

Measurement equipment for compressed air and coolant flow are strongly dependent on the individual throughput rate. In most application cases, e.g. standard milling processes, an air flow rate up to 150 Nm$^3$/h and a coolant flow of 1m$^3$/h can be expected. The most convenient measurement methods for air and gas measurements are given by calorimetric measurement principles, whereas fluid flow meters can be measured amongst other principles by rotameters. Interface standards, e.g. MTconnect, Profinet or OPC, can support the data acquisition in measurements and should be used in monitoring systems to support the usage of available internal machine tool sensors. In most cases auxiliary systems are not connected to standard interfaces and have to be measured additionally by external sensors.

In relation to monitoring, Shaohua Hu [35] introduces an online monitoring approach that is only based on an energy consumption model of the machine tool. The mentioned advantages in this approach, e.g. cost savings and implementation effort, are countered by certain disadvantages, e.g. accuracy in revealed consumption data and interoperability with other machine tool systems. Due to accuracy and reliability reasons as well as reliable monitoring features, screened data cables are important. Radiation or interferences in the measurement can occur, particularly in industrial environments with high voltage. The communication has to be secured against noise, electromagnetic interferences, mechanical stress and chemical corrosion, and data security within the organization as well.

3 METHODOLOGY

According to the generic procedure summarized in chapter 2.2, the following steps are adapted to the requirements of the EVSM approach as follows:

Step 1 - System description

The data required by EVSM is product- as well as manufacturing process-specific. The EVSM defines preliminary system boundaries and can be used as the system overview that must be assessed.

Step 2 - Focusing and definition

This step serves as an approximate comprehension of the system behavior. The revealed data is used in EVSM to aggregate input and output streams from each unit process to an overall picture. The performance can be assessed from a unit process and multi-machine perspective as well as with a focus on single products. The resulting overall system assessment can be used to further analyze the relevance of each process in its potential to contribute to strategic goals of energy savings.

Step 3 - Technical analysis

With regard to energy consumption, all machine tools should be analyzed according to their consumption per product and machine status (idle, set-up, processing). Process and value adding functions can be identified by a product specific energy load profile. The measurements, which are enriched by additional information on the process part time and manufacturing data, reveal critical information for further monitoring purposes. For instance, a relevant monitoring factor is the efficiency assessment in manufacturing. Constant and variable power consumption shares of the manufacturing system, as described by Gutowski [24], must be distinguished for further interpretation in monitoring. Variable power consumption shares are product throughput-dependent. For the interpretation of the efficiency of manufacturing systems, the actual throughput must be determined along to power consumption.

Step 4 - Implementation of monitoring

A monitoring strategy can be developed which is based on the technical analysis, the consideration of the organizations’ requirements and defined goals. A survey among machine tool users [36] revealed that customers are unwilling to invest more than 10% of total manufacturing system costs for monitoring. Furthermore, monitoring activities should evaluate and approve the defined goals of an organization. For this reason the implementation of monitoring systems needs to be performed on the basis of the technical analysis from step 3.
3.2 Case study

In the following case study, measurements of the energy consumption of an entire plant, manufacturing systems and machine tools the above methodology were performed with a Swiss SME specialized in consumer goods.

The focus in applying measurements within the given use case was to detect potential fields for optimization and further monitoring activities. Moreover, the influence of different product groups on the consumption of each machining process was assessed. Figure 5 shows an excerpt of the applied EVSM.

![Figure 5: Extraction of EVSM in use case.](image)

Within the evaluation of the EVSM, 11 key manufacturing processes were identified throughout the entire production facility. Only electrical energy and compressed air were relevant as energy inputs on each manufacturing step. The relevant manufacturing steps, e.g. goods-inspection, milling and grinding, could be separated by manual logistic handling.

![Figure 5: Extraction of EVSM in use case.](image)

Figure 6: Power supply for milling on assessed process.

Figure 6 shows a milling process as an area chart with the compressed air in purple and the electrical input in grey representing the total energy input during the measurement of a reference part. For the EVSM the average values for electricity and compressed air can be calculated during the machining process. The exact processing times can be revealed directly from the measurement or by set up trigger signals from the Program Logic Control (PLC). The measurement further shows some dependencies on the machine tool components, which cannot be further assessed with this aggregated measurement. The peak values that represent transient machine tool activities must be investigated for further relevance.

Further, the assessment of the total manufacturing shows that some consumptions are process-dependent, with a significant variance, or independent, with a constant energetic behavior. On the aggregated EVSM-level power averages and durations can be adopted as static values for further interpretation and simulation. For the optimization of the indicated machining processes, the performed measurements visualize potentials, for instance a high energy share in different machine modes or periodic behavior, but require further investigations and measurements on the component level.

Finally, a total overview of the entire manufacturing energy and resource consumption is given. Fields of actions can be defined for the application of a monitoring system according to the intended targets in optimization.

4 DISCUSSION

The case study has shown that the trade-off between methodological completeness and practical measurements can be solved by applying a straightforward methodology and measurement techniques that reflect the energetic behavior of machining systems. As different variations of manufacturing processes and company-specific strategic goals for environmental improvements are given, the application of the presented methodology requires an approach on a case-by-case basis. The lack of standardization and benchmarking in combination with the low financial motivation for energy efficiency monitoring in production demand individual solutions worked out on the results of the presented methodology.

For the supply of media such as cooling water or process steam, measuring remains laborious due to built-in tubes difficult to access. Preinstalled measuring devices might produce data about the total supply, with insufficient resolution in time in extra efforts for data acquisition and synchronization though.

Requirements explained in the state of the art, e.g. flexible metering which can be moved to different locations on the plant floor, are not necessary if the target is clear and a profound goal definition is made based on pre-measurements. As customers are unwilling to pay high implementation costs for monitoring devices, a pre-measurement can help to reduce costs by focusing on the concrete company targets and desired level of detail.

5 CONCLUSION

The presented approach assists in bridging the gap between requirements of Energy Performance Indicators defined at a strategic level with actual measurement possibilities at the shop-floor level by helping to define a monitoring strategy with adequate measurement points. Furthermore, it supports the macro optimization in enabling sufficient knowledge of energy consumption of the production system. It does not support the micro optimization as further and more detailed measurements have to be performed.

6 ACKNOWLEDGMENTS

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7 REFERENCES


[26] VDI 4602 sheet 1, in Energy management - Terms and definitions2007, Beuth Verlag GmbH.


