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# EVALUATION APPROACH WITH FUNCTION-ORIENTED MODELING OF MACHINE TOOLS

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***Abstract****. Sustainable production, machine tool efficiency optimization, and general machine monitoring are based on monitored machine data. Due to the variety and complexity of machine tools, an enormous amount of data is generated and can lead to uncertainties in further interpretations. Contemporary machine classifications do not meet the requirements of machine energy audits. Up to now, mechanical and electrical components are measured without any reference to their functionality within the system. This paper introduces an approach for the function-oriented interpretation of energy data of a machine tool. This interpretation is independent of the individual machine tool.*

## 1 INTRODUCTION

Energy consumption is a relevant factor in machine tool operation in several respects. First of all, the vast majority of energy consumed by a machine tool results as a thermal impact on the machine; thermal distortion is consequently a primary cause for inaccuracy [1]. Second, this thermal impact demands supplementary measures for heat transfer and thermal stabilization of the machining process and machine tool [2]. Third, energy is and will continue to be a cost factor in manufacturing [3].

Unfortunately, neither the machine tool manufacturers nor their customers have a clear picture of the energy consumption of machines and production lines today [4]. On the grounds of increased competitive pressure, rising prices for energy, possible legal requirements, and further optimizations, a detailed picture of the energy consumption within a machine tool production system is necessary. Systematic measurements of machine tools' overall energy consumption can also contribute to cost awareness and provide a basis for decision-making in manufacturing. Within the life cycle of machine tools, the use phase is the most dominant stage for energy consumption [5]. The energetic evaluations in the use phase are constrained by the assessment of machine tool components and their energetic behavior. This paper introduces a top down evaluation approach for the energetic behavior of a machine tool by applying a functional modeling of the system. This method aims to characterize a complex machine tool system and facilitates optimization and energy efficiency improvement.

## 2 STATE OF THE ART

A universal method of capturing and interpreting the resource and energy consumption is not yet available. The diversity and complexity of machine tools make it difficult to propose a reasonable method. Comparability of the energy consumption and energy efficiency of different process technologies or machine tool configurations can hardly be identified by applying a single component evaluation.

A comprehensive comparability can set a basis for decision-making within manufacturing, i.e., type and quantity of machine tools. Brinksmeier [6] and Kuhrke [7] represent a bottom up approach by taking into account direct process parameters such as cutting force or depth in relation to energy consumption. This approach represents a universal and comparable physical evaluation ground. Direct process energy is not the only energy cluster in a machine tool system, however. Machine internal energy and machine external peripherals are important consumers and relativize this basis for comparison. Dietmair [4] has shown that the major share of a machine tool's energy consumption is load-independent and used by peripheral equipment.

Own power measurements (Fig.1) show that the chip removing energy of a typical hard turning process has minor impact on the total energy consumption. In other cases, the auxiliaries that disprove a common energetic comparison on the component level dominate the total energy consumption. From these findings, a comparison based on the chip-removal energy is not applicable.

Relevant direct value adding functions of the machine tool must be identified for all-embracing energetic optimization, thus defining the favored goal functionality such as chip removal or direct process cooling. Auxiliary components, often with a constant load and power consumption, fulfill essential functionality, but without proportionality to added value. The goal is to define their share and amount in order to minimize the power consumption to the essential physical minimum. Furthermore, their functionality might be substituted by corresponding technologies or proper dimensions in order to increase energy efficiency.

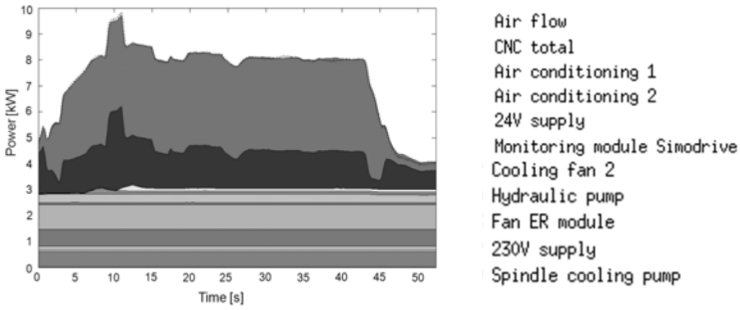


Figure 1 Power measurement of machining a drive shaft on a turning machine with process cooling by compressed air

An abstract view of the overall machine tool system, including the peripheral consumers, could clear up the evaluation statements and conclusions made from the component power measurements. These evaluation statements can be reached by detaching from the component to a functional view of the system. It is an abstract view detached from technical solutions or implemented components.

## 3 CONCEPT OF THE FUNCTIONAL ENERGY EVALUATION

Function orientation is primarily represented in the development of complex technical systems such as in the automotive sector. A review tool is considered to meet consumers' requirements. The development and testing of the defined functionalities can be challenging since complex mechatronic or hybrid systems such as vehicles, buildings, and machine tools fulfill their defined functionality, employed by various consumers. Regarding technical specification, the evaluation of the functionality and its attributes, i.e., energy consumption, shall be done on the component level.

A function is defined as the outcome, task, action, or attribute of an object or component [8]. The functional description is general and independent of the system design. Corresponding components can be mapped to one of five main machine functions, as illustrated below for a generic sample machine tool.

The assignment or mapping of mechanical/electrical machine components to the functions is specific for each case. Fig.2 shows this transition from total energy consumption via functional level and functional mapping to mechanical/electrical component level with hereby defined five main machine functions.

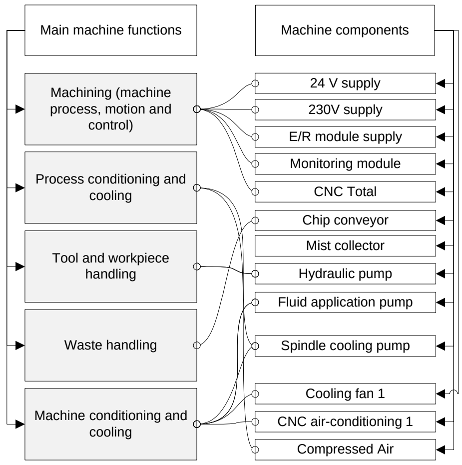


Figure 2 Main machine tool functions and its example components for a lathe

The main machine tool functions on the first level are described in the sequel:

### 3.1 Machining (machining process, motion and control)

This function summarizes the target function of the machine tool, i.e., the energy consumption needed to realize the primary machining process. It comprises for instance the realization of cutting velocity, of an electro-discharge process, or of laser beam for cutting. It also includes machine motion needed during machining, e.g., the energy for the relative movement between a tool and a workpiece. As in most cases, this function is closely linked with and driven by a numerical control. It includes Programmable Logic Controller (PLC), monitoring systems, and measuring systems, except the cooling of these parts. Typical mechanical and electrical components for the function 'machining process, motion and control' are linear and rotary axes of a machining center with their drives, and the numerical control system including the user interface.

### 3.2 Process Conditioning and Cooling

This function, which comprises conditioning, cooling, and heating, is process related. It keeps the temperature and other relevant conditions of the working volume, the tools, the fixtures and/or the workpieces within limits. Process conditioning may be seen as value adding function. This function is directly dependent on the machining process to keep it stable, e.g., lubrication for grinding and die lubrication for forming. Supply and consequently energy consumption may be dependent on the value adding functionality. Furthermore, there might be

some relation to machine cooling (see 3.5) and/or heating. In some cases, the two functions can
hardly be distinguished from each other. A guideline can be the generation of direct added value, i.e. surface quality, or auxiliary functions, i.e., cooling fan for electronics, respectively. Typical mechanical components for the function "process conditioning and cooling" are cooling pumps or compressed air if used for process cooling.

### 3.3 Workpiece and Tool Handling

'Workpiece and tool handling' may consist of changing, grasping, clamping, handling, and lifting of the workpiece, the tool, or both; furthermore, it includes the infeed of raw material and the measurement of workpieces in the machine tool. Typical mechanical components for handling workpieces are robots, hydraulic fixtures, and pneumatic chucks. Typical mechanical components for tool handling include a turret of a turning machine and tool changer of a machining center. In some cases, this function might be separated into two subfunctions: 'workpiece' handling and 'tool' handling.

### 3.4 Waste Handling

This function summarizes the handling of chips, cutting fluids (such as separation and filtering), handling of dust and fumes, and handling of dirt, including the protection of machine components against ingress of harmful waste, i.e., fluids or chips. Typical mechanical components for the function 'waste handling' consist of a chip conveyor, filter systems, and exhaust systems. A common measure to protect components is to seal air for motors and measuring systems.

### 3.5 Machine Cooling and Conditioning

This function summarizes all cooling and heating that is independent from the machining process. The machine cooling and conditioning does not add value to the machining process itself. It is applied to keep the temperature of the control cabinet within operational limits and ensure that components are not damaged or distorted. In some cases, this function can overlap with the process cooling and conditioning. One way to distinguish machine cooling from process cooling is to consider the location. Process cooling is directly connected to the workpiece and process area, whereas machine cooling and conditioning, in most cases, do not have a direct contact to the machine lubrication or active parts (e.g. workpiece or chuck).

## 4 COMPONENTS MAPPING FOR FUNCTIONAL EVALUATION

Various machine tool systems can be characterized based on the above-mentioned definition and classification of these five generalized functions. The main machine functions, i.e., machine motion with the generation of relative movement of axes, can be realized by different technologies, quantity, and the type of components. They are independent of the individual machine tool configuration and dimensions. An abstract view of the system can therefore help to compare similar but not identical machine tool configurations (Fig.2).

Herewith the attributes of each energetic relevant component, that is, power consumption, must be summarized and clustered according to the functional component mapping (Fig.3).

| Specific turning machine | Machining (machining process, motion and control) | Process conditioning and cooling | Workpiece handling and Tool handling | Machine cooling and conditioning | Waste handling |
|---|---|---|---|---|---|
| ... | ... | | | | |
| CNC Total | 1 | | | | |
| Chip conveyor | | | | | 1 |
| Pulse lubrication | | | | 1 | |
| Mist collector | | | | | 1 |
| Hydraulic system | | | 1 | | |
| Coolant pump | | 0.5 | | 0.25 | 0.25 |
| ... | ... | | | | |

Figure 3 Functional mapping with a matrix

The mapping of the components and their contributions to their intended function has to follow general rules, but it must be done individually. Therefore, it needs a methodological approach. The component mapping within the evaluation may differ while it does not influence the total power and energy consumption.

Most components are directly related to one function; for instance, a machining spindle is part of machine motion. In the case of the coolant pump (Fig.3), it contributes not only to process cooling but to machine cooling and waste handling by washing away the chips as well. Consequently, the energy consumption of the coolant pump must be split into these three functions, based on measurement or – more frequently – on estimation. A machine tool energy audit is a good way to estimate these shares. The assigned share of the components defines the ensuing evaluation and optimization. Summing up, the functional energy evaluation can be structured into a general part, which is valid for all machine tools, and a specific part, which represents the individual machine tool configuration (Fig.4).

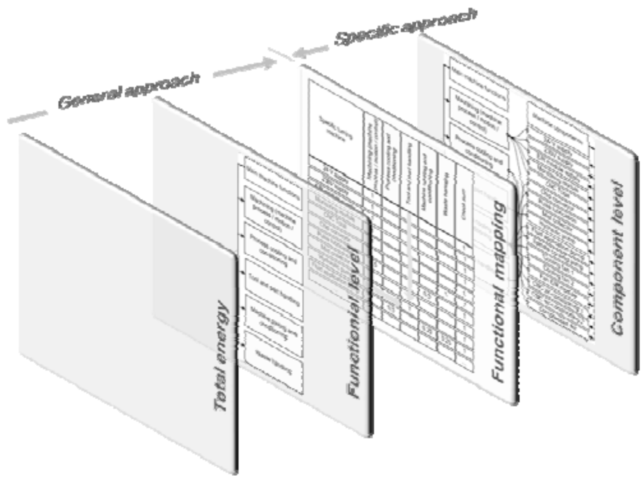

Figure 4 Functional evaluation overview corresponding to Fig. 2 and Fig. 3

## 5 EXAMPLE OF THE FUNCTION ORIENTED EVALUATION

Different machine tools were assessed according to the introduced functional evaluation. Therewith not only milling or grinding machines match this introduced scheme, but also laser cutting or EDM machines. The shown measurement of a typical turning machine, which consists of the components represented in Fig.2, is used as a standard example for this evaluation. The measured reference process, which is an automotive driveshaft, assigns the energetic behavior of the machine tool. The mean power values of each component during one part machining cycle are summarized and clustered according to the functional mapping in Fig. 3 and shown within the functional evaluation in Fig. 5.

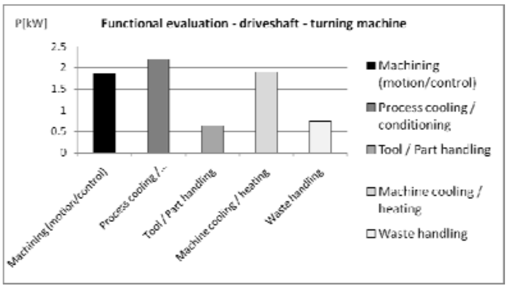


Figure 5 Functional evaluation of a drive shaft on a turning machine

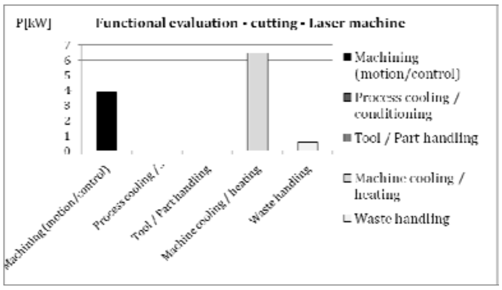


Figure 6 Functional evaluation of a laser machine

The evaluation shows a relatively minor share of power consumption of the main, value adding function 'machining', as expected from Fig.1, whereby the supporting auxiliary functions are dominant. Furthermore, 'process cooling and the machine cooling' dominate in this case.

The disproportion between these functions and the primary function ‘machining’, representing the energy initially brought into the machining process, puts some doubt on the efficiency of these functions. The respective components might be oversized; the technologies and/or the subsystem design might be inefficient. A different but not typical evaluation picture results for the case of dry machining with excessive feed rates and cutting depths, boosting the share of the main function ‘machining’ but leading to massive tool wear in the case of turning processes, as internal measurements have shown

Another functional evaluation represents a typical picture of a laser cutting machine (Fig.6). The main machine function is represented by the CNC drives, the high frequency (HF) generator, and the process gas turbo blower. In this machine configuration, the process cooling and the tool and/or part handling function are not applicable, as there is no need and no consumer to fulfill this function. In the event of an automatic workpiece handling, this function must also be assessed. The machine cooling peripheral is dominant, whereas the waste handling function is represented by a constantly running exhauster. This evaluation can therefore provide an energetic comparison of another machine tool technology that provides the same application, such as metal sheet cutting by punching. This approach is presented in the ISO/WD 14955-1 standard with additional definitions and examples as well.

## 6 CONCLUSION AND OUTLOOK

The functional oriented energy evaluation represents an approach of a conceptual review of machine tools. It helps to understand the energetic behavior of a machine tool and establishes a common basis for comparison, energetic evaluations, and further optimizations. The assessment is made based on total energy consumption and data acquisition, which is attributed to defined machine functions. Therefore, the functional view can be seen as a tool, helping to provide a clear depiction of value adding functions, as well as a sensible clustering of data acquired from a machine tool production system without any disadvantages or loss of information. The advantage is to get a simple, easy to understand picture of the energy consumption. A second point is the obviousness of proportions, leading to the potential field for optimization. Another advantage is the possibility to compare different assemblies of components, either for one machine tool or the comparison of various machine tools, e.g., in decision-making for manufacturing. As it is related to known function-oriented methods in value analysis, target costing, or product development and testing, the concept is easy to adapt and can be implemented in an industrial R&D environment as a complementary tool for energy assessments.

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