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How much energy does precision need?

Adam Gontarz[1], Raoul Roth[2], Thomas Liebrich[2]

[1]SIGMAtools, Switzerland
[2]RhySearch, Switzerland

thomas.liebrich@rhysearch.ch

Abstract
A machine tool mainly consumes electrical energy, but also hydraulic, thermal and pneumatic energy for specialized functions. The efficient use and correct control of these types of energy are crucial for the operation and performance of the machine tool are not rule-based but highly individual and dependent on the machine use, its configuration and parametrization, especially when high demands are placed on the accuracy of the manufactured workpieces.
This article presents the results of a multi-channel measurement in accordance with ISO 14955 on a 5-axis machining center. For this purpose, all energy forms and components in various operating states of the machine tool are systematically recorded and analyzed. The result is a detailed analysis of all system components in all operating states with a focus on process conditioning and the identification of inefficiencies. Based on the measurements carried out, nine measures are defined which have a usage-dependent optimization potential of up to 15 %.

Energy efficiency, machining, energy monitoring

1. Introduction

Increasing energy costs and growing ecological pressure, particularly requirements regarding ESG compliance, call for innovative approaches to saving energy in industrial processes. Machine tools, which play a central role in the manufacturing industry, require hydraulic, thermal and pneumatic energy as well as electrical energy. Optimizing their energy efficiency therefore offers great potential for reducing energy consumption and operating costs, while maintaining or improving productivity and quality, which not only brings economic benefits but also contributes to environmental protection.

The aim of this thesis is to systematically analyze the energy efficiency of a 5-axis machining center and based on this, to identify various strategies for optimization, including the process- and application-specific configuration and parameterization. To this end, the most important influencing factors are identified, various operating states are analyzed, and practical solutions are developed. The study is intended to create a basis for further research and industrial applications aimed at a sustainable reduction in energy consumption.

2. Environmental evaluation of machine tools according to ISO 14955-2:2018

The ISO 14955 series deals with the environmentally oriented assessment of metal-cutting, metal-forming and wood-working machine tools. The aim is to reduce the energy consumption and environmental impact of machine tools throughout their entire life cycle. Part 2 of the standard [1] presents measurement methods for energy evaluation and also contains informative notes on improving the energy efficiency of machine components such as drives, cooling and lubrication systems or hydraulic components, their controls and combinations of machine components.

An important aspect is the definition of the "machine tool" system boundary, which shows the incoming and outgoing energy flows (see Figure 1).

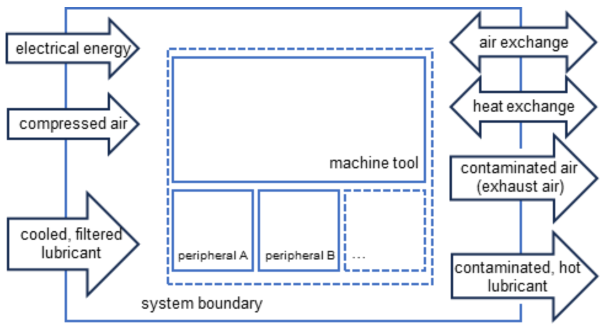

Figure 1. Delimitation of the "machine tool" system with incoming and outgoing energy flows according to ISO 14955-1 [2].

2.1. Measurement setup used in this study

The measurement system used was developed at the Institute of Machine Tools and Production (IWF) at ETH Zurich [3]. It supports the multi-channel measurement of all relevant energy flows within the "machine tool" system boundary and thus fulfils the requirements of the corresponding ISO standard [1]. The energy consumption of all relevant consumers such as motors and pumps are recorded, as well as that of heat exchangers or compressors. The architecture of the measuring system is shown in Figure 2.

2.2. Measured consumers and measurement procedure

The multi-channel measuring system is used to record and synchronize the energy consumption of electrical consumers as well as the compressed air consumption of the machine tool for various operating states. According to [1], the external cooling water supply must also be considered: as several machine tools as well as the room air conditioning are connected to this, direct measurement at the cooling water supply is not possible. However, the relevant proportion of the external cooling water supply is recorded with the machine tool and balanced accordingly.

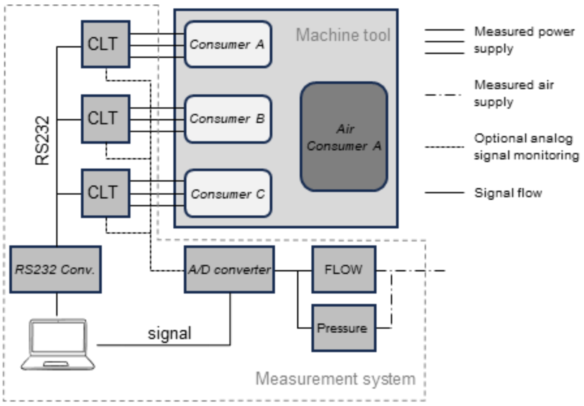

Figure 2. The architecture of the measuring system [3].

The energy consumption is recorded at 18 measuring points (see Table 1). In addition, according to [4], typical machining processes must be defined for the machine under investigation, which are summarized in Table 2.

Table 1. Overview of the various measuring points.

Point of recording	Description
1	Main terminal 400 V DC
2	24 V DC upstream of main switch / fire extinguishing system
3	24 V DC downstream of main switch / fire extinguishing system
4	Control unit
5	Spindle lubrication
6	24 V DC
7	Hybrid unit (oil pressure for hydrostatic bearing / temperature control of cooling water)
8	Exhaustion
9	Heat exchanger
10	Cooling and lubrication system
11	Tool changer, Y axis
12	Tool changer, Z axis
13	Heater of cooling and lubrication system
14	Power converter of dressing spindle
15	Motor of chip conveyor
16	Hydraulic system
17	Pump of cooling and lubrication system
18	Compressed air at main lead

Thus, the defined reference process is not a standard and generally applicable workpiece, but an individual and typical process based on the present machine tool configuration. Here it includes both roughing and finishing processes, as well as different workpiece materials and types of cooling lubrication. The operating states, defined according to [4], are shown in Table 3.

3. Measuring results

The following section presents and compares selected operating states.

Table 2. Overview of the various machining processes.

Machining process	Workpiece material	Process parameters	Cooling lubricant
(i): Roughing	EN AW 2007	n = 30’000 a_p = 25 a_e = 2 v_f = 13’000	Minimum quantity lubrication (MQL), oil
(ii): Finishing	EN AW 2007	n = 39’000 a_p = 0.1 a_e = 0.22 v_f = 2’000	MQL, oil
(iii): Finishing	EN AW 2007	n = 39’000 a_p = 0.1 a_e = 0.2 v_f = 2’000	Flush and internal cooling, oil
(iv): Finishing	EN AW 2007	n = 39’000 a_p = 0.1 a_e = 0.2 v_f = 2’000	MQL, oil
(v): Roughing	1.2083 ESU (annealed)	n = 6’500 a_p = 20 a_e = 0.75 v_f = 2’500	Flush cooling, oil
(vi): Micro drilling	1.2083 ESU (annealed)	n = 20’000 stroke = 5 mm v_f = 5’000	Flush cooling, oil
n...spindle speed in [rpm] *a_p...depth of cut in [mm]*		*a_e...width of cut in [mm]* *v_f...feed rate in [mm/min]*	

Table 3. Overview of the various operating states.

Status	Condition of machine tool	Remark
M01	OFF	No sealing air; no leakage
M02	OFF to STANDY	Activation operation
M03	STANDY	Machine tool in standby; axes in control, no thermal stability required
M04	SETUP	Referencing of axes; spindle run-in; installation of chuck and workpiece including warmup
M05	READY	Machine tool is ready for machining and thermally stable. Consumption of compressed air: ~485 l/min
M06	Machining process (i)	Consumption of compressed air: ~670 l/min
M07	Machining process (i)	Tool change and tool measurement
M08	Machining process (ii)	Process without high pressure operation
M09	Machining process (ii)	Process including high pressure operation
M10	Machining process (iii)	Multi-axis finishing with MQL
M11	Machining process (v)	Process validation measurement
M12	Machining process (vi)	Process validation measurement
M13	EMERGENCY STOP	Manual emergency stop
M14	STANDY to OFF	Deactivation operation

3.1. Operating status M02

The start-up of the machine, from OFF to STANDBY, can have an energetic relevance. The key criterion here is the switch-on and warm-up time of the machine as well as the switch-on sequence of the respective machine components as well as the component function in these particular machine tool states. As can be seen in Figure 3, the machine requires around 3.5 minutes to reach a stable standby state. There is a fluctuation in the cooling and lubrication system; sealing air and hydraulics are active.

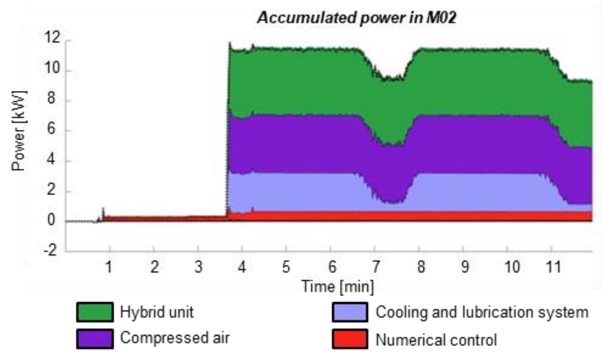

Figure 3. Measurement of operating status M02 (OFF to STANDBY).

3.2. Operating status M03

The standby state corresponds to the operating state when the machine is not producing. According to [2], no thermal stability is required (in contrast to M05). Figure 4 shows that the cooling and lubrication system regulates between 1 kW and 2.5 kW; the sealing air (3.8 kW / 492 l/min) and hydraulics (4.5 kW) remain constant. The drives are controlled and consume around 0.5 kW.

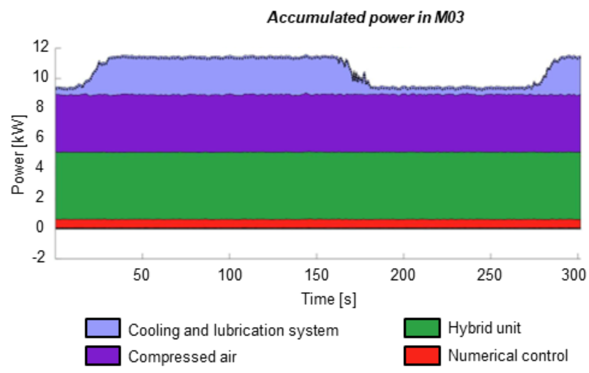

Figure 4. Measurement of operating status M03 (standby).

3.3. Operating status M04

The machine tool is referenced and prepared for the process. Blanks are inserted and measured, and the machining process is prepared. The machine also shows control of the cooling lubricant system and minor activities on the axes and the compressed air (see Figure 5).

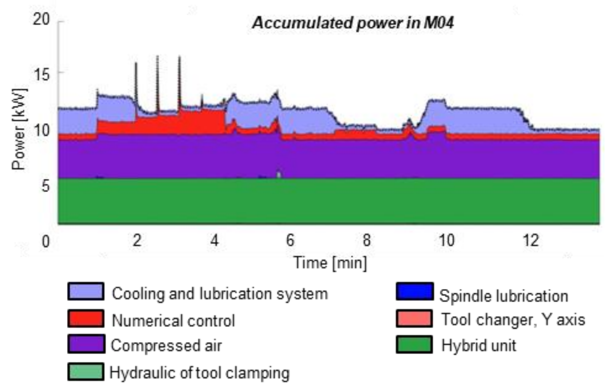

Figure 5. Measurement of operating status M04 (setup).

3.4. Operating status M06

During the process, a higher air consumption and an increase in the performance of the cooling lubricant system can be seen directly in the process. The hydraulics are constant. The extraction system has a slight overrun after the process (see Figure 6).

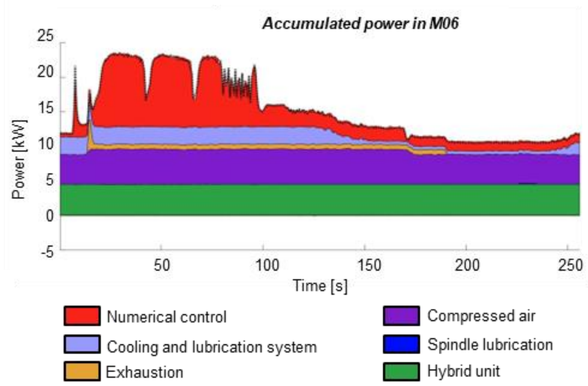

Figure 6. Measurement of operating status M06 (roughing in Aluminum).

3.5. Operating status M08

The power consumption for finishing with minimum quantity lubrication is shown in Figure 7. Compared to M06, significantly less power on the axis is required during the process while the sealing air and hydraulics remain constant.

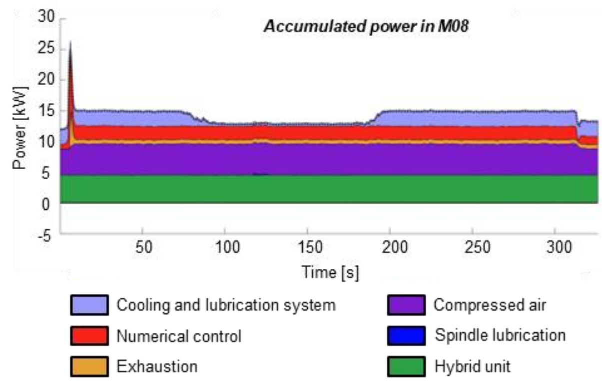

Figure 7. Measurement of operating status M08 (finishing in Aluminum).

3.6. Operating status M13

The measurement from STANDY to EMERGENCY STOP is useful if the machine is operated unmanned and there is a problem in the process, e.g. a tool breakage or in the workpiece supply (e.g. missing bar material). It can therefore happen that the machine remains in this state for an entire empty shift. This operating status checks which components are still active. As shown in Figure 8, there is only a low level of activity on the axes in the emergency stop; all other components are switched off.

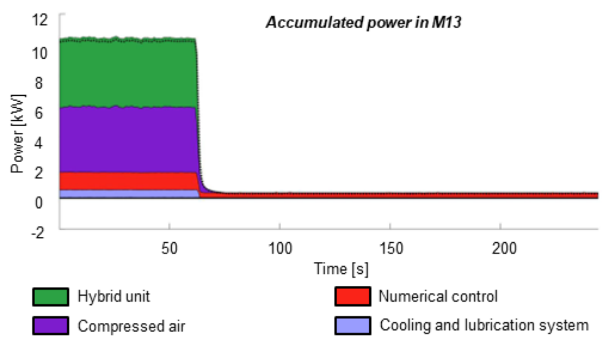

Figure 8. Measurement of operating status M13 (ready to emergency stop).

4. Interpretation and conclusion

In this section, the measurement results are analyzed and possible adjustments are discussed and evaluated.

4.1. Retrofit analysis

The retrofit analysis [5] allows the individual efficiency of the individual components to be determined mathematically using the multi-channel measurement on the reference process.

The retrofit indicator I_r is determined from the independent parameters a_e and a_o. Here, a_e determines the power share of the component compared to the other measured consumers (e.g. 32 % share of total power), while a_o defines the control quality, i.e. the energetic variance (e.g. how constant is the component). The product of the two factors results in the retrofit indicator I_r. The higher this is, the more inefficient the component is.

Table 4. Rating of inefficient consumers.

Ranking	Consumer
1	Hybrid unit
2	Compressed air
3	Exhaustion
4	Control unit
5	Heat exchanger
6	24 V DC
7	Spindle lubrication
8	Power converter of dressing spindle
9	Motor of chip conveyor
10	Hydraulic of tool clamping
11	Cooling and lubrication system
12	Heating of cooling and lubrication system

Compressed air and hydraulics are recognized as the dominant components. Both are very constant and process-independent and comparatively high. These components should be optimized throughout all different machine tool states. A process-dependent extraction system should also be examined.

4.2. Functional analysis according to ISO 14955

This analysis (see Figure 9) makes it possible to describe the energy behavior of the production plant in the reference process and to obtain further indications of possible optimization measures. The power requirement of the respective components is divided into the following five functions:

(1) Machining (machining process, motion and control)
(2) Process conditioning and cooling
(3) Workpiece and tool handling
(4) Machine cooling and conditioning
(5) Recyclables and waste handling

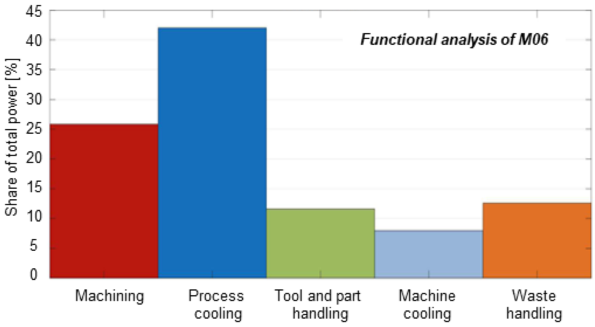

Figure 9. Functional analysis of operating status M06 according to ISO 14955-1.

4.3. Possible optimizations with quantitative assessment

The following measures (see Table 5) can be derived from the measurements carried out:

Table 5. Overview of different possible optimizations

Action	Description	Qualitative assessment
A1	Testing the compressed air activity (sealing air) during start-up (no preceding process)	Recommended action
A2	Testing the hydraulic activity (thermal) during start-up	Recommended action
A3	Testing the cooling lubricant activity during start-up (standby, no thermal stability required)	Action to be examined
A4	Checking a hydraulic accumulator	Non-recommended action
A5	Reduction of sealing air in non-productive states	Action to be examined
A6	Checking an ECO standby without thermal stability	Recommended action
A7	Testing of process-dependent sealing air and hydraulic control	Non-recommended action
A8	Testing a standby similar to an emergency stop	Action to be examined
A9	Checking whether the machine can be switched off during non-productive times	Recommended action

Furthermore, the possible optimization measures are evaluated according to their economic efficiency and amortisation. For this purpose, possible financial savings are calculated based on the assumption of energy costs, average power consumption, the operating time of the machine or the increase in efficiency of the optimization measure. These are then used to calculate the permissible costs of the corresponding optimization measures via the amortization costs. Two and seven years are used for the amortization period.

Based on the current energy costs, which are also dependent on the location of the machine tool, the reduction of sealing air (A1) may cost a maximum of CHF 5,100 if amortized within two years and with 10 % energy savings; with 50 % energy savings, however, it may cost CHF 25,500. Measures on the machine to reduce energy consumption by 10 % may cost a maximum of CHF 18,300 if amortized over seven years, but CHF 91,500 if the energy saving is 50 %.

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