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Framework of a Machine Tool Configurator for Energy Efficiency

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Abstract

The energy consumption behavior of installed machine tools and manufacturing systems are nowadays well evaluated and the field of action for comprehensive improvements and optimization activities is open. Despite the possible improvement potential of installed machine tools, its implementation is limited due to constrains such as high investment costs with unknown amortisation time for the machine tool reconfiguration. The planned configuration of components tailored to the machine tool's target use is seen as a promising way to address the expected energetic performance in the configuration phase using detailed multichannel measurements and knowledge of past improvement activities.

A modular configuration approach, based on multichannel measurements, in order to improve the energy efficiency of the machine tool, including all auxiliaries, is not present yet. In conjunction with a case study, this paper introduces a concept for a machine tool configurator to integrate the requirements for the energy use during the use phase of the machine tool and its components. Beyond this, the paper provides information for TCO calculations and investment decision.

The integrated approach enables machine tool builders to optimize the machine tool configuration, select components in order to increase energy efficiency and achieve cost savings for the machine tool user, in line and validated with the machine tool builder's business case.

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Keywords: energy efficiency; machine tool configuration; power measurement; energy efficient manufacturing, energy consumption, energy model

1. Introduction

Apart from legislative initiatives such as the European directives 2009/125/EC [1] and 2012/27/EU [2], machine tool user and builder have a strong motivation to implement energy efficiency measures in manufacturing as the industrial electrical consumption contributes according to [3] to 42.6 % of the worldwide electricity consumption. Energy savings imply therefore also a notable economic potential. Based on this amount of resources, in particular electricity, manufacturing industries and machine tool builders, have a great leverage on the reduction of energy used and resulting CO_2-emissions.

At the same time, the worldwide manufacturing industries' energy saving potential is estimated by 20% until 2050 [4]. Waste of resources and energy is typically caused by the mismatch of functionalities, over dimensioning, high process reliability margins, poor integration into the manufacturing environment and wasteful operation. Performed energy consumption measurements [5] revealed a trade-off between the machine tool design and the actual machine tool usage. Approaches performed today are characterized by rule-based measures to foster energy efficiency. Based on the strong machine tool individuality in design, usage and machining process it is obvious that a major optimization potential needs to be tackled by a customized approach rather than rule-based procedures. This study aims at paving the way for addressing these issues before their occurrence and in order to fully exploit energy and resource saving potentials of machine tools. Energy efficiency therefore needs to be addressed as

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early as possible in the design phase and with all necessary information on the foreseen utilization of the machine tool.

2. State of the Art

A fundamental basis for the indication of needed energy improvement measure is the application of adequate measurement methods and equipment. Metering devices for power profiling and resource consumption measurement of machine tools enable in-depth information to identify energy efficiency improvements as shown by Kara et al. [6], O`Driscoll et al. [7], Bogdanski et al. [8], and Gontarz et al. [5]. These approaches allow a detailed investigation of the machine tool's power profile for well-known machining processes and applications. Brecher et al. [9] confirm that in most cases machine tools are over-dimensioned as there is poor information on the actual energetic needs or controllability of auxiliaries in relation to the actual machining process. In accordance to the sub-component selection without energy measurements, Schäfer [10] estimates a general performance margin for machine tool auxiliaries of 1.2 to 2 to ensure all theoretically possible load conditions. As a general estimation Abele et. al [11] identified a square proportion of the weight of horizontal lathe to its electric connected load due to dynamic forces and additional cooling auxiliaries. It can be therefore seen, that configuration is important but up to now energy efficiency does not nearly not occur in the early development phase. For instance, over-dimensioning, inefficient construction and machine tool design are caused by missing energy efficiency considerations in this phase. Configuration in manufacturing firstly occurred in the context of mass-customization, introduced by Pine [12]. Salvador et al. [13] introduced an approach to satisfy an increasing demand for customized products, while keeping costs to a minimum. Configuration is referred to as activity to compile a set of pre-defined components taking into account restrictions for assembly [14]. The products complexity is predefined by product specific manufacturing strategy and the degree of specification demanded by the customer. The manufacturing strategy for machine tools is typically make-to-order and enables both: a customer specific configuration before and possible reconfigurable after the purchase of a manufacturing system. Approaches in industry towards reconfigurable manufacturing systems to increase flexibility and productivity have been introduced by Koren et al. [15], Kono et al. [16] and Lorenzer et al. [17].

Approaches such as Design-for-Environment [18], Eco-Design [1] and Life Cycle Assessment (LCA) [19] put holistic, life-cycle oriented design into practice. These approaches allow maximum flexibility in machine tool design, e.g. embedding eco-design guidelines in the development process. Diaz et al. [20] suggest to estimate the constant energy demand of machine tools during design phase and minimize it, if a high power level can be expected. The ISO 14955-1 [21] states fields of action for integrating energy efficiency into the product design process. In general the machine tool can be described as an assemblage of non-controlled or constant, semi-controlled and variable components, e.g. pumps or fans [22]. The energetic behavior of these consumers is characterized by the actual machining process, the machine usage and the production environment. Information on the actual machining process and future machine tool use is not known in an adequate and detailed way in early development stages. For this reason it is obvious that rule-based eco-design methods cannot reveal the full optimization potential and must instead be individually applied based on detailed information to enable all necessary machining operations with an adequate and efficient machine tool configuration.

Reconfigurable machine tools are stated to be more cost-efficient than dedicated ones due to their ability to adapt to changing production requirements. However, approaches of today focus on the manufacturing systems' flexibility rather than on the energy efficiency. Furthermore, their use is limited in industrial setting due to complexity and high implementation costs. The multi-objective optimization approach as introduced by Bensmaine et al. [23] focusses on the usage and change costs of machine tools and tooling. It neglects the operating costs caused by media and energy, e.g. steam, compressed air or electricity. Züst et al. [24] show in their study that most energy efficiency on installed machine tools (retro-fit measures) do not pay off in a considerable period of time (ROI) or even remaining lifetime due to multiple factors, e.g. energy price, machine use, and optimization prize. Even though, configuration is forecasted by the National Research Council [25] to be one out of six key competitive factors in manufacturing, machine tool configuration for energy efficiency is a frequently neglected.

All in all, the right dimensioning of machine tools accomplished by a well-designed configuration procedure is beneficial both in energy and cost savings. A demand for less energy and therefore lower operating costs during machining in combination with lower purchasing investments of adequate designed components is expected according to Ehrlenspiel et al. [26].

3. Approach

The following approach was developed to tackle the challenging trade-off between the right investment decision before the machine tool assembly and installation, and an adequate and reliable machine tool configuration for the intended machine use. The following four successively applied elements (Figure 1) are seen as mandatory for an energy efficiency optimization through machine tool configuration and design:

- A multichannel metering system to evaluate the entire energy flow picture of the machine tool with its components.
- An optimization procedure based on the customer specification and individual needs, e.g. the use over time and use intensity.
- A configuration logic which transforms the specific machine tool user needs into modular optimization measures.
- A modular design kit system determined by the machine tool design that enables the adjustment of energy intensive components according to the machine tool user's specification.

A multichannel metering system (1) which is able to evaluate all required energy forms, e.g. electrical power, compressed air and cooling fluids, on a detailed component level allows indicating the right dimensioning and control settings of machine tool components during the machine tool use phase. This system is indispensable to determine the actual optimization potential, because it reveals dependencies between components, mismatch and over dimensioning. The multichannel power metering system serves as a base for the optimization of existing machine tools as well as the development of configuration strategies and a modular design kit system, leading to a new business model for energy efficiency implementations in manufacturing.

The machine tool optimization procedure (2) empowers the machine tool builder to implement minor improvements on the machine tool in both: use phase and configuration phase. This includes also a decision tree, as published by Gontarz et al. [27], in order to indicate which components are recommended to be switched off during unproductive, e.g. standby, taking into account their energetic impact as well as safety, work piece quality, and process reliability. However, this method requires repeated, varied attempts for solution finding, which is time consuming, costly and today lacks integrating experience gained form the past.

These shortcomings are overcome by the development of a configuration logic (3) that considers optimization decisions taken in the past and translated to empirical, generic set of proven component combinations individually adjustable to the machine tools' intended use. Experience based optimization decisions can be made due to the defined use scenarios of the machine tool, e.g. the scale of production and related time shares of the operational states "off", "standby", "ready" and "process", as well as the expected load intensity of manufacturing process. This approach is mainly reasonable in the configuration phase.

Nevertheless, there are some boundary conditions besides energy that limit the configuration freedom, e.g. the basic machine tool design and the interfaces between the machine tool components. In order to fully exploit the energy efficiency potentials the configuration logic needs to be translated to a modularization system (4) that allows both an adjustment and exchange of energy intensive components. Thusly, the dimension and control capability of energy intensive components such as the cooling system, exhaust air and compressed air system can be matched to the user's specification and the machine tool's intended use. The limits of configuration are determined during the design phase due to the definition of the interfaces between components and the resulting restriction of assembly.

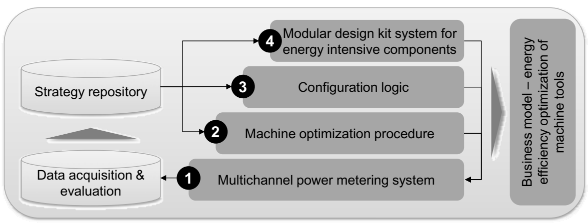

Figure 1: Four-step approach towards energy efficiency optimization through machine tool configuration and design.

The challenge is to obtain the information required in order to apply the optimization strategies. In order to foster energy efficiency holistically, four types of information have to be obtained from the customer before machine tool configuration:

- **Manufacturing environment-knowledge:** Connection to the technical building service, e.g. compressed air, transportation, cooling fluids, steam, exhaust air system, interfaces with the building, e.g. air temperature, noise level, vibrations.
- **Operations-knowledge:** Process type, e.g. specification of standby, idle and processing times.
- **Machine functionality-knowledge:** part geometry, process steps, quality, process requirements, e.g. temperature stability requirements, cooling.
- **Component dimensioning-knowledge:** Process intensity, e.g. part material, part geometry, process parameters such as cutting speed and feed rate.

4. Industrial Case Study

The case study is derived from the bilateral project Energy Efficiency for Customer quotation (EE4C) in cooperation the machine tool builder Fritz Studer AG and illustrates the energy efficiency optimization procedure based on the elements (1) and (2) of the before introduced four-step approach (Figure 1). The project aimed at intensifying the interaction between the machine tool builder and machine tool user in order to improve the energy efficiency in the machine tool use phase. The key component is represented by the multichannel measurement principles in combination with the machine tool configuration in the quotation phase. The quotation enables a suitable phase for the machine tool configuration, which can be adjusted according to the individual customer needs. Therefore this four-step approach leads to awareness of the energetic machine tool behavior, an improved energy efficiency performance and an optimized total cost of ownership (TCO).

1. Process definition: In the first step the machine tool user provides the product or product range defining the machining process. It is essential that the machine tool user can specify the required product in type, quantity and quality or set of desired applications. If a defined machining process is not given or unknown, an internal test work piece (Figure 2) is considered; covering and assuring all required product and quality features of the selected machine tool.

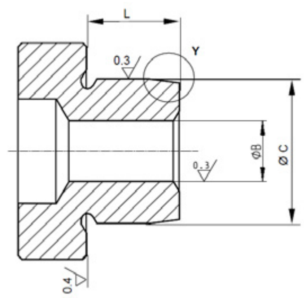

Figure 2: Sample of an internal grinding test piece for detailed machine tool measurement.

Furthermore, this internal test workpiece is designed to fit on all available machine tools for internal comparison and simulates the most common customer machining process.

2. Machine tool measurement: In the second step, the detailed machine tool multichannel measurements based on the customer machining process is performed. This is not needed if the standard workpiece is used (Figure 2). With the multichannel measurement system, the power consumption profile of each component and all necessary additional resources, e.g. compressed air and cooling liquids, are evaluated. This measurement also covers the component control dependency towards the machining process and thermal behavior of all active machine tool components as well as all possible machine tool modes, e.g. “off”, “standby”, “ready” and “process” mode. Figure 4 shows the performed machine tool measurement for a test work piece and based on the test machine tool in standard configuration.

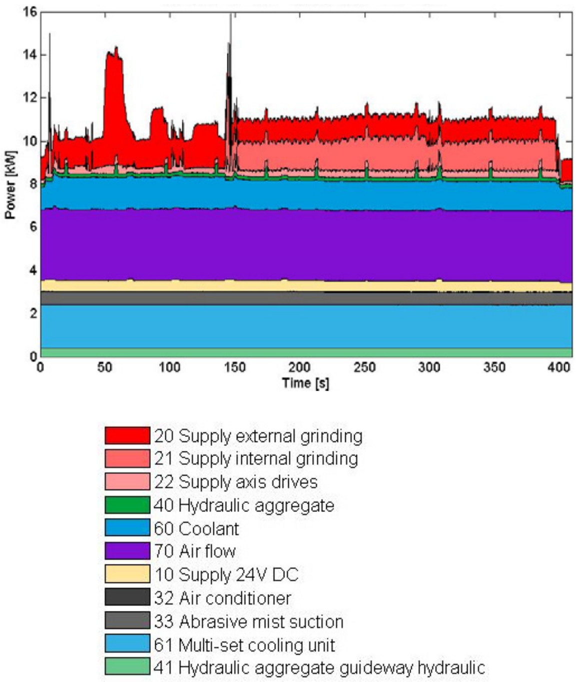

Figure 4: Detailed machine tool measurement based on specific customer requirements in standard configuration.

3. Analysis and economic evaluation: Based on the performed measurements in (2), inefficiencies on the component level based on the actual customer machining process and expected machine use can be indicated. Thus, different machine tool use scenarios can be simulated, e.g. shift regimes, machine states duration and occurrence, etc. In the given case and according the performed measurement and expected machine tool use, frequency controlled cooling pumps as well as an optimized standby mode are reasonable and further considered. For the specific case those optimization procedures reveal an optimization potential. This approach is represented with the step 2, introduced as overall approach in chapter 2 (Figure 1). On the basis of the selected technical optimization measures economic evaluations, e.g. Net Present Value (NPV) and Return on Investment (ROI)

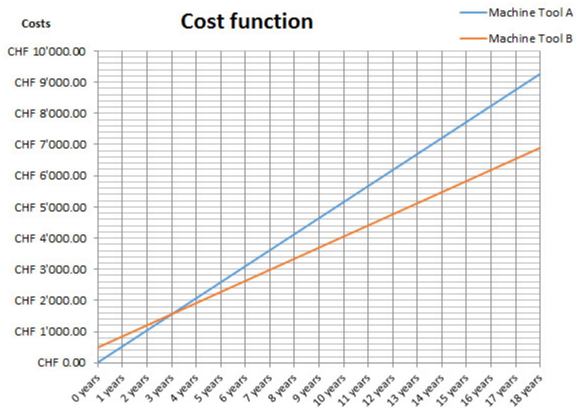

Figure 3: Return on investment calculation and comparison between machine tool setting A and B.

(Figure 3) have been performed.

4. System selection: In the final step the pre-selected standard machine tool configuration can be modified based on the analysis in step (3). Based on the measurement and the possible technical optimization, the machine tool user receives a detailed TCO calculation of the machine tool in standard and modified configuration. Both configurations, the standard and optimized configuration, are set up to perform according to the specified customer requirements with first priority to product quality and quantity. For a lean implementation of this approach in future, a pre-configuration of the machine tool should be made based on historic data and detailed component simulation (compare chapter 2, Figure 1, step 3)
In the present case study, the modified machine tool configuration led to a direct energy consumption reduction of 20% with an amortization time of the additional costs of 3 years.

5. Discussion and Outlook

Machine tool builders today do not consider energy efficiency during the configuration phase, although this phase allows a high degree of customization with an adequate cost-benefit ratio, potentially providing competitive advantage for both, machine tool builders and users. A higher degree of customization requires a design to order manufacturing strategy, enhanced by an additional methodological approach.

The introduced approach is based on the detailed machine tool measurement in combination with the right application time and suitable configuration procedure. It introduces an effective way for the highly individual machine tool configuration. This approach is further designed to tackle the individual customization, based on different parameters, e.g. machine use, machining process. The given approach represents a first step into the modular and customized configuration, but has to deal with lacking information on the customer side. Furthermore, the machine tool user receives a detailed technical and economical machine tool evaluation, which is in line with today's legislation proceeding requiring quantified improvements. For this reasons, this approach will be further considered and improved as a lean process investment in early phases, e.g. quotation phase.

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