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Integrated methodology for the evaluation of the energy- and cost-effectiveness of machine tools☆

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ABSTRACT

Sustainable machine tools are characterized by less consumption of energy as well as low costs during their life-cycle. In order to design such machine tools an evaluation of the energy-efficiency and the costs incurred is needed. In contrast to this, up to now there has been no fully developed evaluation method relating to both technical and cost efficiency of machine tools. Thus, the paper presents an integrated approach for the evaluation of machine tools consisting of methodological proposals for the measurement of energy consumption, modeling of energy flows and simulative analysis of the energy saving potentials as well as an energy-oriented life-cycle costing concept. Additionally, braking energy storage systems and reactive power compensation are analyzed. Based on the identified energy saving potentials, it is shown that at present only reactive power compensation is economically profitable under given assumptions.

1. Introduction

In order to ensure sustainable production and environmental-friendly use of machine tools (MT), customer demands for productivity, flexibility and cost-effectiveness are requested in a global competition. With resources dwindling and energy prices rising, the energy consumption of MTs is an increasingly important factor with respect to ecological as well as economic targets. Efforts to reduce this consumption are reasonable, considering the indication of an energy saving potential of manufacturing systems and processes of 30% in the automotive industry and the production of white goods [1].

Consequently, the European ECODESIGN Directive 2009/125/EG requests energy saving of new goods, including MTs [2]. Accordingly, considerable effort is made in science and industry to develop MTs or to adjust existing ones with the aim of reducing energy consumption while maintaining performance and cost-effectiveness. For this reason, the draft standards ISO 20140 "Environmental and energy efficiency evaluation method for manufacturing system", ISO 22400 "Key performance indicators for manufacturing operations management" [3], CECIMO "Self-Regulatory Initiative" for energy-efficient MTs [4] and ISO 14955 "Environmental evaluation of machine tools" [5] are under development. Additionally research activities by the CIRP CWG EREE [6] and CO2PE! [7] are noted. Moreover, some basic research results are provided by the eniPROD ("Energy-efficient Product and Process Innovation in Production Engineering") Cluster of Excellence [8].

This paper presents a novel methodology for the evaluation of the energy- and cost-effectiveness of machine tools which is characterized by the integration of energy flow measurement, predictive energy consumption simulation of drive systems and life-cycle costing. Section 2 gives an overview of the methodology, its pillars and their interfaces. Section 3 provides procedures for the measurement of the energy consumption as a basis for deriving energy-saving priorities and supporting further technical and economic investigations with an energy-related database. Section 4 describes a model of energy flows in drive systems which was developed to enable simulative analyses and applies this model to the evaluation of the energy-saving potentials of braking energy storage systems and reactive power compensation. Afterwards, Section 5 presents an energy-oriented life-cycle costing concept that is used for the economic evaluation of the proposed technical measures using the results of the energetic evaluations. Thus, the methodology allows for a targeted design and decision-making concerning energy-related investments from a technical as well as an economic perspective. Section 6 summarizes the findings and gives an outlook.

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2. Overview of the methodology

The methodology proposed is characterized by the combination of different technical and economic evaluation pillars (see Fig. 1). As part of the technical evaluation, the measurement of energy consumption is used to reveal the energy flows and consumptions in components of MTs. The data derived this way can be used in the various steps of the problem-solving procedure; in particular, they allow the identification of the main energy consumers representing starting-points of efforts to improve energy-efficiency. Besides, the data form a basis for the modeling and simulation as well as for the economic evaluation.

Using modeling and simulation, design alternatives of identified main consuming components or functions can be analyzed with respect to potential energy savings. This is possible virtually and, thus, in a time- and cost-efficient way. The verification of these models can also be based on the data from the measurements. Modeling and simulation contribute to the problem-solving procedure as well. In particular, they help to identify design alternatives leading to higher energy-efficiency.

The design alternatives that are advantageous with respect to energy consumption will then be subjected to an economic evaluation focusing on the life-cycle cost. Therefore, the technical/energy-related data derived from measurements and simulations are used and complemented by economic data, such as prices, e.g. for energy, additional up-front costs, etc. that influence the life-cycle cost of the MT. After the decision based on the different evaluations and the realization of the chosen measures, a verification of the energy-savings is possible using measurements. And, if required, a new cycle of evaluation and problem-solving may start.

The technical and economic evaluation of machines is a complex and demanding task due to various design alternatives, influencing factors and long time-periods that have to be considered. Thus, in order to perform the evaluation in a structured and consistent way it is recommended to use a procedure model, as it is shown in Fig. 2. This model consists of two levels: the machine tool-level and the submodel-level. On the "higher" MT-level, the MT as a whole is evaluated with respect to technical/energetic and/or economic criteria. In a subordinate submodel-level, evaluations can be made referring to MT components or processes within the MT. The results of these evaluations provide a basis for the improvement of specific components and processes and contribute to the evaluation of the whole MT.

At both levels the overall evaluation procedure is subdivided into six steps. In the beginning, the target figure(s) and the basic evaluation method (step 1) as well as the system boundaries and evaluation period(s) (step 2) have to be defined. Afterwards, the MT can be modeled and analyzed (step 3) and its relevant environmental conditions investigated (step 4). At the MT-level this will typically lead to the identification of relevant evaluation subtasks (e.g. as regards the components and functions of the MT) and a turn to the submodel level. In step 5, further relevant data have to be gathered and forecast, until the target figure(s) are calculated and sensitivity analyses are conducted in the last step (referring to the influence of specific variables, uncertainty, etc.). The use of the procedure model for systematic technical as well as economic analyses will be presented in the following.

3. Energy consumption analysis and measurements

The aim of energy consumption analysis is to specify the energy flows within the MT, depending on power consumption and operating time. The following approach for energy analysis focuses on energy consumption of MTs in different modes of operation in order to identify main energy consuming components and functions and priorities of their energy-reduction; it is not focused on the optimization of manufacturing processes and process time. The methodology described below is based on the procedure model (Fig. 2) and is exemplarily applied to cutting MTs.

3.1. Step 1 – definition of target figure(s) and basic evaluation method(s)

At the first step (**M1**), energy consumption of a cutting MT is defined as target figure. The main energy sources for this object are electricity and compressed air. The first one dominates the environmental impact of MTs at their entire life-cycle with a share of more than 90% [2]. Therefore the following considerations focus on this kind of energy. Energy within material flows will not be considered.

The evaluation is based on the input-throughput-output (ITO) model with energy as input and process energy and energy losses as output (Fig. 3). In general, measurement can be used to record actual energy consumption, while simulation is usable to calculate actual and additionally expected consumption data. The results of measurement and/or simulation are aggregated to energy

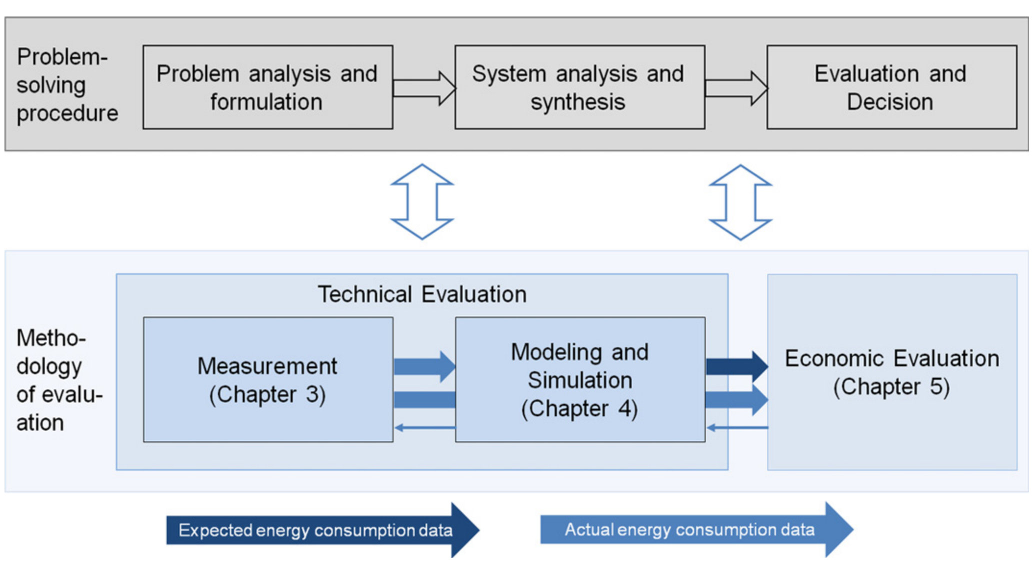

Fig. 1. Methodology for the technical and economic evaluation of MTs.