Special Interest Group Meeting on Precision Engineering for Sustainability
Kern Microtechnik GmbH, Bavaria, Germany, October 2024
www.euspen.eu

Framework for identifying effective measures to improve the energy efficiency of machine tools

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Abstract
This research paper presents a framework designed to systematically identify and prioritize efficient energy-saving measures for machine tools. The methodology encompasses the identification of energy inefficiencies, a detailed cause-and-effect analysis, the development of targeted energy saving measures, and the prioritization of these measures based on their potential impact, feasibility, and ease of implementation. By addressing both technical and organizational aspects, the framework aims to optimize energy consumption, reduce production costs, and minimize energy-related CO_2 emissions. The proposed framework offers a practical and effective solution for enhancing energy efficiency in the manufacturing sector.

Energy efficiency, Machine tools, Framework

1 Introduction

Energy efficiency in production is a critical issue for both companies and society, encompassing ecological and economic perspectives. Enhancing energy efficiency not only mitigates harmful environmental impacts but also optimizes production costs c_P and boosts the competitiveness of manufacturing firms. Consequently, the optimization of energy consumption within the production environment has been a focal point of research for several decades. Despite the ongoing transition in many OECD countries from manufacturing to the service sector, the industrial sector's share of total energy consumption is projected to grow by an average of 0.4 percent per year from 2010 to 2040 [1]. This underscores the significant potential for measures aimed at increasing energy efficiency in the manufacturing industry, which can substantially reduce energy consumption and energy-related CO_2 emissions, maintaining their relevance in the coming decades. Energy efficiency can be increased on the levels of process, machine, line and factory [2]. Research on enhancing energy efficiency in manufacturing has resulted in numerous technological advancements, such as the development of energy-saving machine tools [3,4], optimized process parameters [5], and energy efficient production planning systems [6].

Given the multitude of technological and organizational solutions for enhancing energy efficiency, there is a lack of transparency in identifying and implementing suitable solutions specific to each company. This necessitates the development of appropriate methods and strategies that facilitate an adapted evaluation of these solutions. First research works focused on developing standardized methods for evaluating the energy efficiency of machine tools [7]. The results have been compiled in various guidelines such as ISO 50001 and ISO 14955-1 [8, 9]. Further research efforts were performed to develop strategies for selecting energy-efficient machine tools, aiding companies in the procurement process [10]. However, existing methods do not provide a standardized approach for evaluating energy efficiency measures applicable to existing production environments and machine tools comprehensively.

2 Framework for identification of efficient energy saving strategies

The methodology presented in this paper was developed to systematically identify potential measures to improve the energy efficiency of machine tools, quantify the savings potential, and estimate the implementation costs. The outcome is a prioritised list of measures based on their anticipated cost-effectiveness. The methodology comprises the following steps (1) Identification of energy inefficiencies, (2) Cause-and-effect analysis, (3) Identification of potential energy-saving measures, and (4) Prioritisation of energy-saving measures. The goal of the developed methodology is to enable an accurate assessment of energy-saving measures with minimal data and labour input. The framework of the methodology, along with the required input data and activities, is illustrated in Figure 1.

2.1 Identification of energy inefficiencies

Detecting inefficiencies is the first step in the methodology for identifying efficient efficiency measures. A detailed structural analysis of the machine tool and the manufacturing process is required in order to understand the energy flows and to identify the relationships between components and sub-components as well as between components and influencing factors from the manufacturing process. As shown in Figure 2, the machine tool should be modelled in as much in detail as possible into individual energy-consuming subsystems and components. It is important to clearly define the system boundaries of the analysis. Furthermore, the direct and indirect energy flows should be quantified as accurately as possible. The accuracy of this step has a major influence on the quality of the assessment result. However, a precise structural analysis requires a good database of the components and their energy flows as well as a great deal of work. Differentiated energy data acquisition is

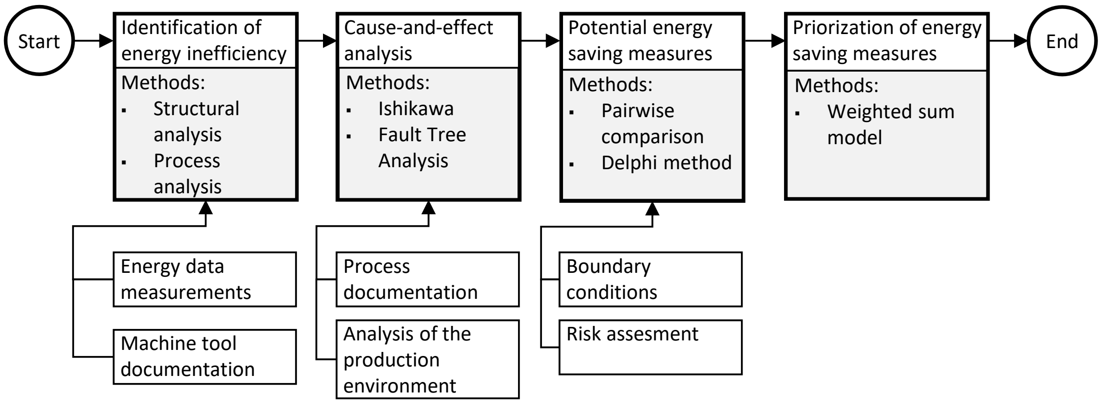

Figure 1: Model of the framework for identifying energy efficiency measures

therefore optimal. If the measurement of energy data is not possible, the documentation of the machine tool can serve as a first point of reference.

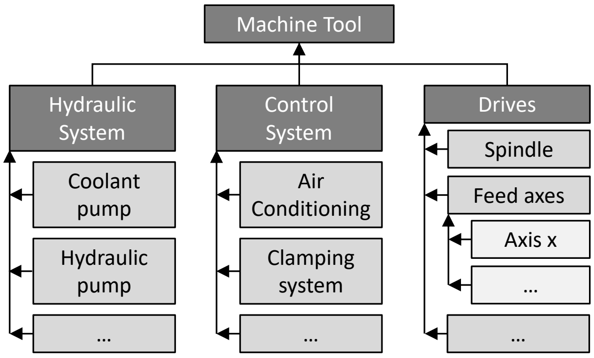

Figure 2: Structural analysis of a machine tool

2.2 Cause-and-effect analysis

To determine the impact of internal and external factors on energy consumption, a comprehensive analysis of the production processes is essential. Structured approaches such as Ishikawa or fault tree analysis should be used to analyse complex technical systems in depth. The Ishikawa system shown in Figure 3 is recommended to capture the relevant factors as it allows a systematic breakdown into the elements of personnel, machine, environment, material and method. If significant variation in the performed processes occurs, an individual analysis of the cause-and-effect relationships for each specific process becomes necessary. This approach facilitates the precise identification of specific factors influencing energy consumption. The factors provide the basis for the development of targeted energy saving measures. The structured analysis of influencing factors ensures the identification of existing factors and prompts a critical evaluation of established procedures within the production process. As a result, this approach reveals potential savings that might otherwise go unnoticed by users.

2.3 Potential energy saving measures

In this phase, targeted energy saving measures are developed to address the identified causes of energy consumption, aiming either to eliminate the root cause or mitigate its effects. The measures must be specific, actionable, and are categorized into technical, process, and organizational measures. The performance of the measures is analysed in terms of the three indicators expected impact on energy consumption C_C, probability of occurrence of the addressed energy inefficiency C_O and ease of implementation C_I. For each measure, a comprehensive description of the required activities is developed. Additionally, existing boundary conditions that may constrain the applicability or efficacy of the interventions are thoroughly analysed. A subsequent risk assessment is conducted to identify potential impacts and conflicts of the measure on the machine tool, production process, and other energy efficiency measures. Alongside the identification of energy inefficiencies and the cause-and-effect analysis, the detailed documentation of every measure facilitates the evaluation of their impact on energy consumption and the potential energy savings achievable. This documentation is also used to assess the estimated ease of implementation. Furthermore, the probability of occurrence of the addressed cause is derived. The detailed analysis is used to quantify the performance values v_C, v_O and v_I with regard to the three indicators C_C, C_O and C_I. To achieve more significant results, methods such as pairwise comparison or Delphi method should be applied in this step.

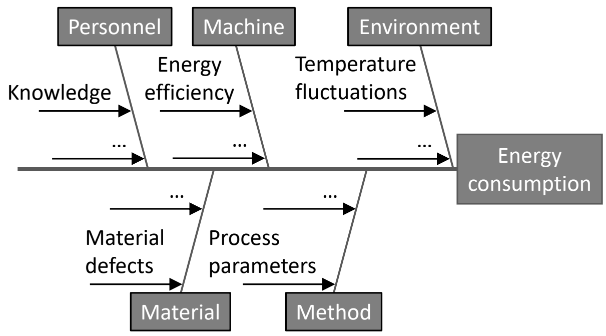

Figure 3: Exemplary cause-and-effect analyses

2.4 Prioritisation of energy-saving measures

The developed measures are evaluated using the previously analyzed indicators and an energy priority index EPI is calculated. The weighted sum model is used to perform a structured and systematic evaluation and selection of energy efficiency measures. Relative weightings w_C, w_O and w_I are assigned to the indicators C_C, C_O and C_I. The energy priority index EPI of each measure m is calculated according to Formula (1) as the weighted sum using the performance values v_C, v_S and v_I.

$$EPI\ (m) = w_C \cdot v_C\ (m) + w_O \cdot v_O\ (m) + w_I \cdot v_I\ (m) \qquad (1)$$

The energy priority index EPI enables a standardised comparison between the measures developed. Measures with a high probability of occurrence of the addressed energy inefficiency C_O, a significant impact on energy consumption C_C and a high ease of implementation C_I achieve a high energy priority index EPI and should be implemented first. This prioritization enables targeted and rapid implementation of successful energy efficiency measure. Systematic evaluation and prioritization ensure that the measures are not only theoretically effective, but also practically feasible and efficient.

3 Challenges and limitations of the methodology

The presented methodology employs a four-stage approach, with initial steps focused on assessing energy consumption and its underlying causes, while subsequent steps are dedicated to the development and prioritization of efficiency measures. A major challenge in identifying energy inefficiencies is the quantification of energy flows. To ensure a realistic assessment of the savings potential and a high level of significance for the prioritisation results, the energy flows must be quantified as accurately as possible. However, achieving a detailed recording of energy flows often necessitates substantial metrological effort. Current investigations include the development of simple mobile measurement solutions for energy recording shown in Figure 4, and the exploration of energy flow analysis via machine control systems and communication protocols such as OPC-UA.

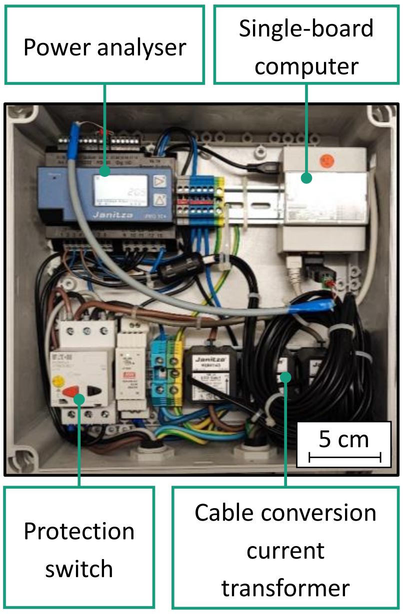

Figure 4: Mobile energy measurement solution for machine tools

Despite the importance of energy savings in production, inherent energy monitoring remains limited in modern machine tools. There is considerable potential for the development of new technologies based on data-driven analyses to further enhance energy-saving production processes.

Another limitation lies in the precise execution of the cause-and-effect analysis, which demands a high level of expertise and consideration to accurately identify existing correlations. Engaging external experts can mitigate the risk of overlooking critical factors, thereby avoiding blind spots. Comprehensive documentation of the causes of energy inefficiencies is essential for the targeted development of measures aimed at enhancing energy efficiency. Only when the causes of energy inefficiency are fully understood can effective and strategic measures be formulated to address the root causes of energy inefficiency.

4 Conclusions

The developed framework for identifying efficient energy-saving measures in production provides a structured and systematic approach to enhancing energy efficiency. By accurately assessing energy inefficiencies, performing detailed cause-and-effect analysis, and prioritizing targeted measures, the methodology enables the effective deployment of the most impactful and feasible energy-saving solutions. While challenges such as the quantification of energy flows and the need for expert analysis remain, the framework's comprehensive documentation and evaluation processes ensure that the most efficient measures are identified and implemented, thereby optimizing production costs and reducing energy-related CO_2 emissions.

5 Acknowledgements

This project is co-financed by the European Union with funds from the European Regional Development Fund.

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