Joint Cost and Environmental Assessment of Tool Replacement Strategies Under Imperfect Wear Monitoring in Milling

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The management of cutting tools directly affects machining costs, environmental impact, and product quality. In industry, tools are typically replaced after a fixed operating time. Although simple and conservative, this practice often discards functional tools, increases machine downtime, raises production costs, and amplifies environmental impacts, since each tool has a non negligible manufacturing footprint.

A more efficient approach is to equip machine tools with sensors that monitor tool condition and enable replacement only when the tool approaches the end of its life. This tool condition monitoring strategy can reduce machining costs by 2–30 % [1,2]. Monitoring may rely on cutting force signals or tool image acquisition systems [3], and models such as Cox PH [4] or Bayesian approaches [5] can estimate wear. Recent studies show that artificial intelligence based models outperform traditional ones, reaching wear estimation errors below 15 % [6,7].

Evaluating the economic and environmental performance of a replacement policy requires information on both aspects. While optimized tool replacement has been studied for steel machining [8], different strategies have not been compared. This work therefore provides a combined economic and environmental assessment of several tool replacement strategies for Ti6Al4V milling to support data driven industrial decisions.

To carry out this assessment, a simulation model is developed. This model consists of three key components: cutting tools, a CNC machine, and Ti6Al4V workpieces. The cutting tools are modelled with variable lifespans drawn from a Weibull distribution, and their degradation trajectories are reconstructed using a hyperbolic sine function, as in [9]. The machine is represented as a medium sized CNC unit consuming a constant amount of energy during machining. The workpiece is assumed to be a high added value component that is machined according to the specifications defined by the selected cutting tools. The quality of the produced workpiece depends on the condition of the cutting tool during its machining. A workpiece is classified as "scrap" if the tool wear exceeds 300 micrometres at the end of machining; otherwise, it is considered "good". Each of these components is characterized by its cost and CO_2 equivalent emissions, as reported in the literature.

Three tool replacement strategies are evaluated:
Scenario 1. Fixed period replacement, reflecting common industrial practice.

Scenario 2. Replacement based on imperfect wear monitoring, allowed only between workpieces.
Scenario 3. Replacement based on imperfect wear monitoring, also allowed during machining.

Each scenario is optimized: replacement time in Scenario 1, and wear thresholds in Scenarios 2 and 3. The results show that Scenario 1 is the least efficient. Scenario 1 has an average production cost of 16.20 EUR per part, whereas Scenarios 2 and 3 achieve average costs of 15.64 EUR and 14.80 EUR, respectively. Using tool-condition-based replacement therefore has a positive impact on the economic cost of machining operations.

Similar conclusions can be drawn for the environmental impacts. This reduction is mainly due to the fact that, to produce the same total number of parts (scrap and good), the tool-condition-based strategies generate fewer scrap parts. This decrease in scrap reduces the raw-material cost as well as the tool cost when results are normalized per produced part.

In general conclusions, the economic performance of maintenance strategies is closely tied to how cutting tools are managed. The method most commonly used in industry, replacing the tool after a fixed machining time (Scenario 1), proves less efficient than strategies based on imperfect monitoring of tool wear. When the tool can be replaced between the machining of two parts (Scenario 2), condition monitoring reduces the economic impact by $3.5\,\%$ and the environmental impact by $1.5\,\%$. These improvements increase to $8.7\,\%$ and $8.1\,\%$, respectively, when tool replacement is allowed during the machining of a part (Scenario 3).

These results clearly highlight the benefits of integrating tool-condition monitoring. However, since the model represents a simplified version of a real production system, several additional factors must be considered in practice, such as the cost and integration of monitoring equipment, the potential for false alarms, the resulting downtime, and other implementation-specific challenges that were not captured in the simulation.

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