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Research article

# Sensitivity analysis of dry machining using a Life Cycle Assessment approach

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ABSTRACT

Manufacturing processes, particularly machining operations, contribute significantly to the environmental footprint of the industrial sector, primarily driven by the consumption of critical resources such as lubricants, tools, and electrical energy. However, the large number of machining parameters and the difficulties of modeling industrial products have always limited analysis of the environmental impact of the process. This study aims to provide a comprehensive understanding of the environmental impact during dry machining. The overarching goal is to contribute to the development of strategies to mitigate the environmental consequences of these manufacturing processes. To achieve this objective, a Life Cycle Assessment (LCA) was conducted to quantify and analyze the environmental impact, using the Environmental Footprint 3.0 calculation method. The central idea is to highlight the often-underestimated contribution of tool wear to the overall environmental impact of the machining process, whereas in the literature electrical energy is the most studied source of consumption. The methodology involves an analytical model, and an experimental test designed to quantify the resource consumption, with the conduct of a sensitivity analysis to determine the machining parameters and scenario influence on the distribution of environmental impact. While electricity consumption traditionally dominates discussions of environmental impact in machining, results of the study reveal a significant contribution from tool wear in the environmental impact ratio, according to specific environmental indicators. The preponderance of this contribution is favored when the values of cutting conditions or tool radius /number of teeth are increased. Depending on the values of the cutting conditions, the scenario and the environmental indicator, the proportion of tool wear in the environmental impact ratio can vary from 5% to almost 90%. In terms of global environmental impact, cutting speed is the most influential parameter, varying by more than 2 times the minimum value for each environmental indicator. A precise definition of the scenario and consideration of the machining parameters are therefore essential to assess the environmental impact of machining correctly. This study also underscores the importance of considering tool wear in the environmental impact of dry machining, which plays an important role depending on cutting conditions, especially cutting speed.

## 1. Introduction

The industrial sector contributes significantly to global greenhouse gas (GHG) emissions [1]. Material removal processes (machining processes) represent the majority of manufacturing methods for mechanical parts. Although the consideration of the environmental impacts of these processes is not recent, the interest in the sustainable development of these processes has recently accelerated. Scientific work on this issue dates back to the 1990s, including studies by Byrne [2], who explored strategies to make machining processes cleaner, and Munoz [3], who proposed the first comprehensive characterizations of the environmental impact of these processes from analytical models. These characterizations consist of quantifying the consumption associated with the machining processes. Several studies establish that electrical energy is the main source of consumption of machining processes [4], and, therefore, the influence of other sources of consumption (lubricants, tools) is neglected. The objective of this paper is to quantify these different consumptions experimentally for a typical machining operation and to analyze their share in the environmental impact of the process. Therefore, an analysis of the life cycle of the process must be carried out. This implies the modeling of consumables and the quantification of their consumption during the machining process. To achieve these objectives, Life Cycle Assessments (LCA) specific to

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**Nomenclature**

| | |
|---|---|
| LCA | Life Cycle Assessment |
| E.F. | Environmental Footprint |
| GLO | Global geographical location |
| RoW | Rest-of-the-World geographical location |
| RER | European geographical location |

consumables have to be conducted or have been conducted in the literature.

The LCA of a process is inherently more intricate than analyzing a manufactured product [5,6]. Evaluating the appropriate functional unit becomes more challenging [7] since the rendered service is not always explicitly defined in cases of process. Defining the study scope and determining the study boundary can be subjects of discussion, particularly concerning estimating the lifetime of the system and the associated allocation rules [8]. Given that a manufacturing process is a dynamic product that evolves over time [9–11], its functionality can change and consequently its provided service. There is a strong need to assess the environmental impact of a process to identify potential action levers to reduce their environmental impacts [12].

Firstly, the literature review is performed with the analysis of machining LCA works already conducted. Secondly, the process leading to the establishment of the model is presented. Finally, the last paragraph is devoted to the experimental results and the sensitivity analysis of the proposed model.

## 2. Literature review

### 2.1. Machining and consumptions

Machining processes by material removal can be performed in different ways, the most common being turning, milling and drilling. The principle consists of using a cutting tool that, coupled with the spindle rotation speed, allows removal from different materials, from plastic to refractory materials.

The literature has introduced several criteria for measuring the environmental impacts of these processes, up to the point of standardizing the energy performance of machining, especially the machine tools used [13–15]. It enables the description of several points to standardize the environmental criteria in relation to experimental measurements. The ISO 14955-1 standard [13] describes exhaustively the different points of energy reduction, mainly on the machine tools design, but also gives recommendations on which strategies to optimize. The different techniques for measuring energy consumption are described [14], and even standardized tests are described based on the average power readings according to the machine tool phase [15].

Many studies have investigated the resource consumption during machining using the LCA method. Most studies focus on the consumable LCA whether it is the tool [16–18] or the lubrication [19–21]. They demonstrate some accuracy of analysis in conjunction with presenting experimental results, but do not provide a comprehensive view of the environmental impact of the process. Pereira et al. [22] couple the lubrication characterization to the power consumption and allowed an impact distribution to be visualized, but neglected the tool wear in their system boundaries according to Pusavec et al. work [21]. The comparison between consumables has been observed in other LCAs but they are limited to screening LCAs to illustrate their experimental results, without developing uncertainty calculations [23,24]. In the same format, Narita et al. [25] propose a numerical evaluation of the machining process consumption, but only for a single environmental indicator (Climate Change). Zanuto et al. [26] provide a complete screening LCA with different system boundaries and impact categories, but the LCA characterization of consumables still needs to be clearly defined. An analysis of the use of lubrication will be carried out, but the study will focus on dry machining, which suits the 42CrMo4 steel used experimentally.

### 2.2. LCA of dry machining

Sustainability approaches have been already applied to dry machining, mainly to the turning process. This process eliminates the need for off-material times during cutting, making it easier to separate types of electrical consumption for analysis. Many studies focus on optimizing cutting conditions and quantifying consumption (electrical energy, tool, workpiece material, etc.) without comparing them with environmental indicators [27,28]. In some cases, a sustainability criterion may be used, but this leads to mono-criteria or qualitative conclusions [29]. Several works actually use an LCA approach. Fernando et al. [30] and Vukelic et al. [31] provide essential screening LCA perspectives but lack detailed consumable analyses and uncertainties studies. Khanna et al. [32] provides a comprehensive investigation with detailed LCA, specifically exploring the impact of different lubrication techniques on turning processes. Nevertheless, a major limitation lies in the oversight of tool production, a critical contributor to the overall environmental impact of dry machining processes. This study seeks to add value by addressing the shortcomings of these studies on dry machining with a LCA approach.

### 2.3. Added value

The goal of the study is to correctly analyze and predict the environmental impact of dry machining, using a complete and transparent LCA approach. A fortiori, a further objective is to contribute to the development of strategies to reduce the environmental impact of these manufacturing processes.

The scientific contribution of this paper lies in rectifying the shortcomings of prior research by demonstrating that the consumption of tool and electrical energy represent major and non-negligible sources of impacts during dry machining. Compared to other LCA studies of dry machining, this paper provides an uncertainty and sensitivity analysis of the environmental impacts, in order to propose only indicators with a sufficient accuracy to be interpretable. The proposed method enables the inclusion of a substantial, though not exhaustive, list of machining parameters in the predictive model. This provides insights into their impact on the overall environmental impact and the respective proportions of different consumables contributing to it.

The objective is to characterize the dry machining process itself, not a resulting workpiece from this process. Henceforth, the volume of machined material is not taken into consideration within the defined boundaries of the studied system. The functional unit is defined as the dry machining of a specific quantity of 42CrMo4 steel (144 $cm^3$) employing a designated toolpath strategy (zig–zag scanning strategy). A singular operation is considered in 2023, within the European region.

## 3. Methods

### 3.1. Applied methodology

The Simapro software version 9 [33] was employed for all modeling activities, utilizing the Ecoinvent 3.8 database [34] for sourcing input data. Certain data were derived from manufacturers data collections, while others were adjusted to suit the specific geographical area under study. The Environmental Footprint (E.F.3.0) [35] calculation method was employed to compute all environmental indicators. Considering that the study pertains to a geographical area within Europe, it was deemed more pertinent to adopt this method, which currently has a consensus within the European scientific community. The decision to employ the E.F.3.0 method stems from the application case context in

Europe. It is acknowledged that certain indicators may be controversial, however this research primarily focuses on the methodological aspects of evaluating a machining process rather than engaging in discussions regarding indicator selection.

The uncertainty calculation was performed using the pedigree matrix [36], detailed in Table SM1 of the supplementary material, to estimate data quality. The incorporation of this methodology [37] along with the basic uncertainty factor is inherent in the utilization of the Ecoinvent database. The purpose of this calculation is to justify using certain cutting conditions compared to others during machining. A lognormal distribution is employed to prevent negative values, and is inherent to the assessment system (pedigree matrix). In fact, the software used (Simapro) converts any input distribution to a lognormal format. In the study, the Ecoinvent Unit data was employed, and for specific data, the Weidema matrix was utilized to adapt each input and output flow. The analysis was conducted utilizing the Monte Carlo analysis function within Simapro. To ensure relevance, a total of 10,000 runs were performed in accordance with the recommendation of Liu [38].

### 3.2. System boundaries

To carry out the LCA of the machining process, system boundaries of the study must be established. The LCA focuses on the local scale of a machining operation. All elements associated with the machining process that have negligible wear in relation to the duration of an operation (machine tool elements, tool bodies, etc.) are therefore not considered. This is consistent with ISO 14955-1 [13] which concludes that only the machine tool use phase is relevant to consider when studying the environmental impacts associated with machining processes. Since the objective is to study the consumables specific to the process, the quantity of material used for the manufacturing and the chip valorization will not be studied in the LCA.

To carry out machining processes several resources are consumed. The major source of consumption during machining is electrical energy. The number of components in machine tools makes it complex to model consumption by component [39]. However, the total measurement of the energy consumed is achievable by measuring the power consumed directly by the machine tool, including all the auxiliary components to the process (numerical control, fans, etc.). The use of lubricant, which is consumed by evaporation in contact with the cutting zone at high temperature but also by losses (splashes, cleaning, capillary action on the chips, etc.), constitutes a significant source of environmental impact in view of its chemical composition. In addition, the consumption of material, characterized by tool wear during machining, represents an important factor in terms of environmental impact, particularly due to the short life of cutting tools. In order to avoid introducing the resharpening factor of monobloc tools in the calculations, only tools with cutting inserts are considered. The consumption of cutting inserts reflects a percentage of wear as a proportion of the mass of the insert consumed. The boundaries of the study are summarized in Fig. 1.

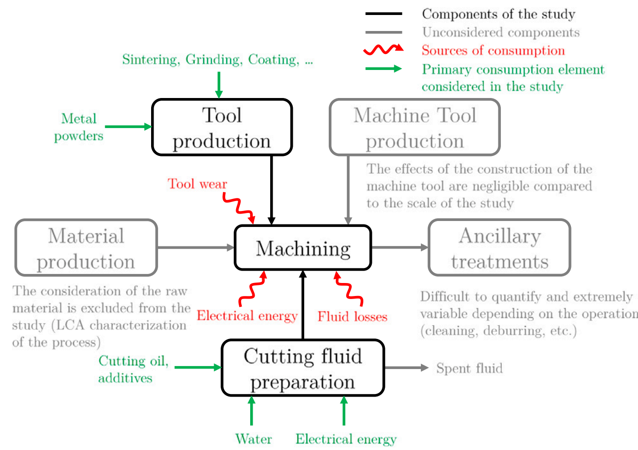


**Fig. 1.** System boundaries of the study.

### 3.3. LCA of consumables

#### 3.3.1. Electrical consumption

The consumption of electrical energy is directly related to the electrical energy production technique, especially the associated geographical area. Since electrical energy consumption represents the majority of consumption associated with machining, either intrinsically to the process or within the lubricant and tool manufacturing processes. The LCA scenario will have a major influence on the interpretation of the results. This aspect will be discussed in Section 4.5.5.

#### 3.3.2. Lubricant consumption

The most commonly used lubricant or cutting fluid is an emulsion of a cutting oil concentrate and chemical additives in water. For Minimum Quantity Lubrication (MQL) machining, the oil concentration can be greatly increased, even to a full extent. Milling is an intermittent process that generates high temperatures at the cutting edges. Cooling with lubrication can cause thermal shocks and cyclic stresses, leading to premature tool wear. Dry milling is recommended for 42CrMo4 steel to prolong tool life, as it maintains temperature variations within acceptable limits for carbide grades. While MQL may be an option, its environmental impact is assessed as negligible compared to other consumption sources (tool, electricity). Additionally, modeling the LCA of lubricants is challenging because the formulations are protected as industrial secrets.

#### 3.3.3. Tool consumption

The production of cutting inserts is separated into 2 main types of consumption. The production of the powders that constitute the insert represent a large part of the environmental impact associated with the use of cutting tools. They are composed of a base of tungsten carbide (WC) with cobalt (Co) as binder. Several additional powders based on niobium, tantalum, titanium, etc. can be added to give the tool specific mechanical properties [40]. The other aspect is the energy consumption related to the tool production. The different phases of cutting insert production are detailed in Fig. 2.

## 4. Results

Several aspects must be detailed in order to correctly identify the environmental impacts of the cutting insert production chain:

- Tungsten carbide production is already characterized on EcoInvent in a study applied to China [44] and a more globalized one [41] that compares to the previous study. Taking globalized data will be discussed in Section 4.5.5.
- Most of the data for rare metals is also globalized, which will raise a question of the data robustness for the study scenario. In terms of alloys, Cobalt is the most commonly used metal in cutting tools, with its environmental impact quantified in EcoInvent [42].
- For grinding and stirring the powder mixture, an organic solvent (heptane) and paraffin are considered added to bind the powder mixture, and then evaporated by drying. The volumes used are estimated from previous studies [41].

**Table 1**
Life cycle inventory modeled of dry machining consumables.

| Input/Output | Parameter | Unit | Value | Uncertainties | Criteria | Region | Comment |
|---|---|---|---|---|---|---|---|
| INSERT | Insert mass 1.6559 g | [g] | 1 | Lognormal | 1.05 | | 30% WC-Co powder losses into solid waste [41] (Lognormal, 1.25) |
| Input | Ammonium Paratungstate | [mg] | 992.5 | Lognormal | 1.05 | GLO | Data source [41] |
| Input | Carbon black | [mg] | 51.4 | Lognormal | 1.05 | GLO | Data source [41] |
| Input | Cobalt | [mg] | 261.5 | Lognormal | 1.21 | GLO | 20% Cobalt distribution in the WC-Co powder, data source [42] |
| Input | Compressed air (700 kPa) | [$dm^3$] | 1.09 | Lognormal | 1.05 | RoW | Data source [41] |
| Input | Electricity | [Wh] | 15.6 | Lognormal | 1.05 | GLO | For tungsten powder production, data source [41] |
| Input | Electricity | [Wh] | 3.9 | Lognormal | 1.24 | GLO | For WC-Co powder production, data source [16,17] |
| Input | Electricity | [Wh] | 149.4 | Lognormal | 1.24 | RER | For insert production, data source [16,17] |
| Input | Heptane | [mg] | 801.7 | Lognormal | 1.25 | GLO | Data source [41] |
| Input | Nitrogen | [mg] | 53.6 | Lognormal | 1.05 | RoW | Data source [41] |
| Input | Paraffin | [mg] | 53.6 | Lognormal | 1.25 | GLO | Data source [41] |
| Input | Selective coat, PVD | [$mm^2$] | 92.2 | Lognormal | 1.11 | RER | Energy consumed by the process [16,17], data source [43] |
| Output | Ammonia | [mg] | 98.6 | Lognormal | 1.49 | | Emitted to air, data source [41] |
| Output | Carbon dioxide | [mg] | 13.5 | Lognormal | 1.05 | | Emitted to air, data source [41] |
| Output | Nitrogen | [mg] | 3.6 | Lognormal | 1.05 | | Emitted to air, data source [41] |
| ELECTRICITY | | [kWh] | 1 | | | RER | Electricity consumed during machining |

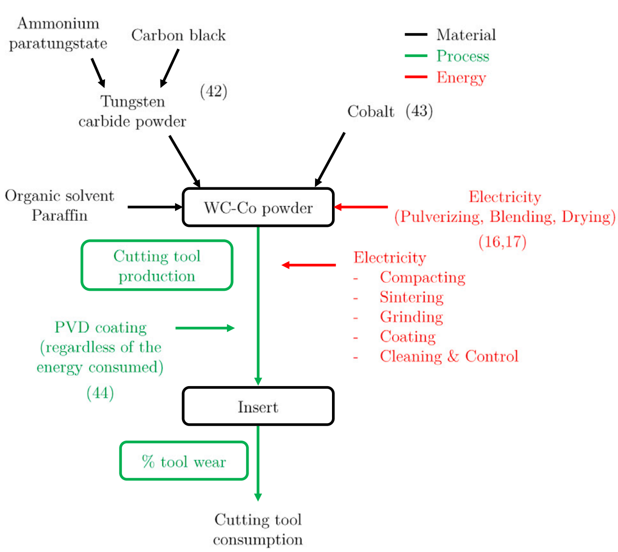


**Fig. 2.** Cutting tool production scenario.

- The whole energy consumption aspect of the insert production chain has been studied theoretically [18] but also quantified experimentally at the CERATIZIT industrial site in Austria [16,17], which will be used for the study. As the processes used are similar depending on the type of powder used, the assumption that the energy consumed is independent of the powder recipe is assumed.
- The coating processes could be characterized directly by EcoInvent [43]. All emissions and consumption related to the coating process are therefore extracted from the EcoInvent database. However, the electrical energy considered for the study is taken from the experimental study of Karpuschewski et al. [17].

### 4.1. Experimental protocol

The objective is to experimentally verify the distribution of consumption in terms of environmental impact. The machine tool is a Mikron HSM600U equipped with a Heidenhain ITNC 530 numerical control and TNC Scope software, which allows various machine data to be displayed, such as the electrical power consumed recovered with variable-frequency drives of the machine tool. The cutting tool is milling tool (SECO R217.69-1616.3-09-A) with SECO XOMX090304TR-ME06 F40M 1-insert test (T1) and 2-inserts test (T2) shown in Fig. 3. The chosen material and associated tool demonstrate favorable characteristics for dry machining. The operation is a face milling of 80 × 90 $mm^2$ rectangular cuboid workpiece. The zig–zag toolpath

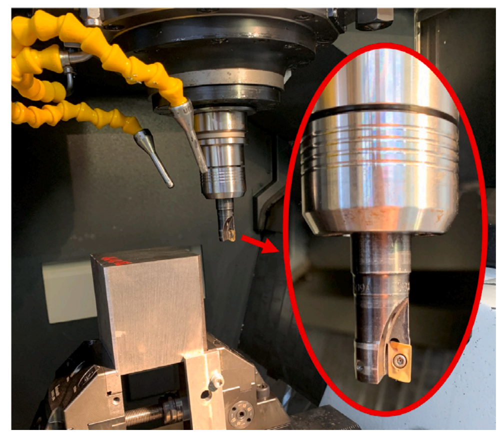

**Fig. 3.** Set-up for the experimental tests.

strategy employed is the most conventional one, aligning with standard practices in the field, with a lateral engagement of 93.75% over a depth of 10 mm. The fixtures are the vice GARANT Xpent 36 1100_0 with clamping modules GARANT 361124_100 and hard front jaws GARANT 361142_100. The depth of cut is 2.5 mm, the cutting speed is 200 m/min and the feed rate is 0.112 mm/tooth. The cutting parameters are designated with regard to technical constraints (usage interval recommended by the carbide manufacturer) and environmental impacts reduction. While the article does not explicitly delve into the selection process, a decision support algorithm has been developed to choose cutting conditions with reduced associated environmental impact.

### 4.2. Scenario retained

The LCA scenario has been defined for a machining process performed in the European region, in 2023. Most of the data in EcoInvent will therefore be assumed according to European studies (RER) when available. As this LCA is intended to be applicable to several geographical areas and is not restricted to a localized region, the transport impact of finished products is not considered in the study. The system boundaries are shown in Fig. 1 in Section 3.2 and the summary of the LCA inputs/outputs is presented in Table 1, with detailed pedigree matrix values in Table SM2 of the supplementary material. The WC-Co powder production being characterized on a globalized study, it is assumed that it is produced in a globalized framework and that the inserts manufacturing is done in Europe. It is then necessary to separate the electricity from a global mix for the powder production and the electricity from a European mix for the insert production (Table 1).

**Table 2**
Results of the environmental analysis and uncertainties for T1 and T2.

| Impact category | Electricity [unit/kWh] | Insert [unit/g] | Uncertainties T1 Low [%] | Uncertainties T1 High [%] | Uncertainties T2 Low [%] | Uncertainties T2 High [%] |
|---|---|---|---|---|---|---|
| Climate change [kg CO2 eq] | 3.76E−1 | 9.22E−2 | 8.2 | 9.4 | 8.0 | 9.0 |
| Ozone depletion [kg CFC11 eq] | 2.32E−8 | 7.29E−9 | 19.7 | 32.9 | 20.0 | 34.7 |
| Photochemical ozone formation [kg NMVOC eq] | 8.12E−4 | 3.27E−4 | 10.8 | 15.8 | 11.8 | 21.1 |
| Particulate matter [disease inc.] | 5.65E−9 | 9.17E−9 | 17.1 | 28.6 | 18.5 | 30.7 |
| Acidification [mol H+eq] | 2.01E−3 | 1.31E−3 | 9.2 | 10.8 | 10.4 | 13.2 |
| Eutrophication, freshwater [kg P eq] | 3.89E−4 | 1.41E−4 | 56.7 | 193.4 | 55.1 | 180.1 |
| Eutrophication, marine [kg N eq] | 3.55E−4 | 2.41E−4 | 11.3 | 14.8 | 12.4 | 18.3 |
| Eutrophication, terrestrial [mol N eq] | 2.98E−3 | 4.08E−3 | 14.7 | 21.2 | 17.2 | 26.5 |

### 4.3. Experimental results of consumption

Fig. 4 shows the measured experimental consumptions of the test carried out. The error bars correspond to the uncertainties related to the measurement and not those related to the repeatability of the experiment. Machining time of the tests are respectively 352.2 ± 1.3 s for T1 and 175.7 ± 0.5 s for T2. The consumption of the cutting tool cannot be directly measured experimentally through tool wear, as it does not reflect consumption proportional to the insert utilization time relative to its service life. To measure the percentage of insert utilization, these measured machining times must be converted into tool/material contact time. For this purpose, an analysis of the toolpath strategy and its non-cutting times is carried out. Coupled with the cutting conditions and the volume of material machined, this tool/material contact time can then be obtained. The ratio of this time to the tool life, specified by the carbide manufacturer for the given cutting conditions, and the number of usable cutting edges, indicates the proportion of tool utilization to its tool life.

As for the power consumption, the magnitude order of the power consumed is kW, the measurement uncertainty lies in the variability of the measured power. The variations of power observed for a nominal regime are mainly null. Some consequent jumps of measurements disturb the value of measured power, which has repercussions on the value of final consumed energy. Several standardized tests have been carried out to determine the effective measurement uncertainty of the electrical power consumed. The experimental results for measured power indicated a standard deviation of the data of 172 W.

Initially, tool consumption due to tool wear was to be measured directly by the wear observed on the tool edge. Although the tool wear rate is considered proportional to the operating time of the tool, in fact tool wear follows a non-linear law. After rapid initial wear of the cutting insert, the steady-state wear phase does not allow for any significant evolution of experimental wear to define a relevant wear rate, particularly when machining 42CrMo4 steel with carbide tools [45]. The experimental wear rate is therefore determined by the machining time in relation to the tool life claimed by the carbide manufacturer for the given cutting conditions.

### 4.4. LCA discussions

The associated indicator values and uncertainties are listed in Table 2. The uncertainties are slightly altered because the ratio of consumables to total impact is different between the two tests T1 and T2. The percentage distributions of the indicators for the different consumption sources are presented in Fig. 5, with their associated proportional uncertainties. Contrary to what has been found in the literature, the environmental impacts assessed, other than those associated with electrical energy consumption, are not negligible. Between the two tests, the proportion of tool consumption is similar, because for T2 the material time is distributed over the two inserts, but two of them are worn out. As for energy consumption, for T2 it is approximately halved for all components other than the mechanical energy developed by the cutting, which is practically the same for the two tests. All uncertainties are reasonable except the freshwater eutrophication, with an uncertainty of more than 100%, whose relevance may be questionable. Other E.F.3.0 method indicators [35] give much higher uncertainties (Table SM3 of the supplementary material) and have been considered non-relevant for the study.

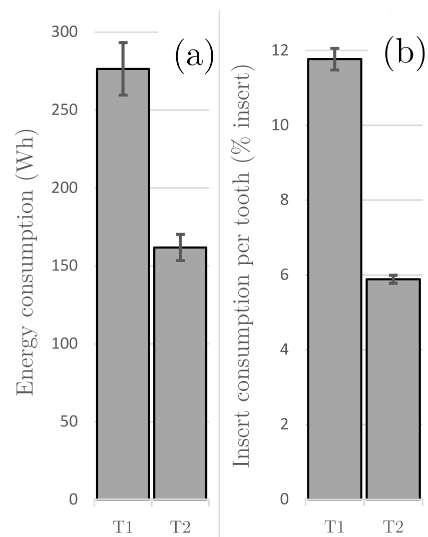


**Fig. 4.** Quantification of experimental consumptions: (a) Energy consumption; (b) Proportion of insert utilization.

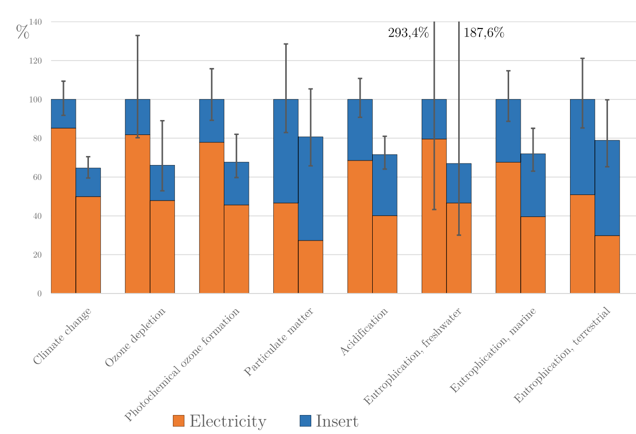


**Fig. 5.** Environmental analysis of the dry machining tests.

### 4.5. Sensitivity analysis

This section provides a sensitivity analysis of machining parameters on the share of the consumables environmental impact (electricity, tool). An analytical model presented in substance has been developed to predict the associated environmental impact.

#### 4.5.1. Analytical modeling

Considering the different components of the study, the modeled environmental impact ($I_{total}$) is determined by summing all the elementary impacts considered in the research, including tool wear, axis, spindle, elements consuming energy in the steady machine state, and the load corresponding to the mechanical power developed by the cutting process (Eq. (1)).

$$I_{total} = I_{tool\ wear} + I_{elec\ axis} + I_{elec\ spindle} + I_{elec\ steady} + I_{elec\ load} \tag{1}$$

The dry machining sources of consumption need to be modeled in order to conduct a theoretical sensitivity analysis. The consumption of electrical energy $E_{tot\ elec}$ is characterized by the instantaneous power of the various machine tool components $P_{elec\,i}$, integrated during machining time $t_{mach}$ (Eq. (2)). The mechanical power developed by the cutting is also represented as electrical power consumed.

$$E_{tot\ elec} = \sum_{i \in components} \int_0^{t_{mach}} P_{elec\,i}(t) \cdot dt \tag{2}$$

The consumption of the cutting tool is represented by its wear during use. Tool life $t_{life}$ is simulated using the generalized Taylor tool life model [46]. The insert consumption $U_{insert}$ is expressed as a tool wear factor of the tool/material contact time $t_{tool/material}$ with respect to the tool life and its number of usable cutting edges $N_{cutting\,edges}$ (Eq. (3)).

$$U_{insert} = \left(t_{tool/material} / t_{life}\right) / N_{cutting\,edges} \tag{3}$$

#### 4.5.2. Sensitivity analysis of consumables on the global environmental impact

Experimental tests have shown that cutting conditions, as well as tool radius/number of teeth, affect not only the consumables ratio, but also the total environmental impact value. Fig. 6 shows the evolution of various environmental indicators, normalized to their proper minimum value, as a function of cutting speed $V_c$ (feed rate $f = 0.112$ mm/tooth, depth of cut $a_p = 2.5$ mm, radial depth of cut $a_e = 93.75\%$, tool radius $R = 8$ mm, number of teeth $Z = 2$). For low cutting speed values, the overall environmental impact will tend to increase sharply, as the associated machining time will be longer. Even if tool wear is minimal at such cutting speeds, energy consumption is much higher. On the contrary, at higher cutting speed values, the overall environmental impact will also tend to increase significantly, as tool wear is accelerated at such cutting speeds. The associated reduction in power consumption is not sufficient to stem the increase of the overall environmental impact. It can vary by more than 2 times the minimum value for each indicator, depending on cutting speed. Within the cutting range recommended by the carbide manufacturer, the evolution of the indicators is essentially identical, but there are disparities at the cutting speed value which generates the minimum associated impact. This multiplicity of environmental indicators, which are not quantitatively comparable with each other, prevents real optimization of this cutting parameter.

#### 4.5.3. Sensitivity analysis of cutting conditions on the environmental indicators

Tool wear and electrical energy consumption vary greatly according to cutting conditions and machining time. For dry machining, the sensitivity analysis can be analyzed as a ratio of one of the two sources of consumption (tool wear in this case) to total consumption. Fig. 7 shows the evolution of cutting conditions independently of the others that are set (Cutting speed $V_c = 200$ m/min, feed rate $f = 0.112$ mm/tooth, depth of cut $a_p = 2.5$ mm, radial depth of cut $a_e = 93.75\%$, tool radius $R = 8$ mm, number of teeth $Z = 2$). Cutting speed is the most influential cutting condition on the consumption ratio (Fig. 7.a), as it is the cutting parameter with the greatest impact on tool wear [46]. As cutting speed values increase, tool wear is accelerated, while electrical energy consumption is reduced. For the radial depth of cut (Fig. 7.b), increasing this parameter reduces the number of side passes in the toolpath strategy. This increase leads to a reduction in machining time (a fortiori electrical energy consumption), and therefore to a higher share of tool consumption in the environmental impact ratio.

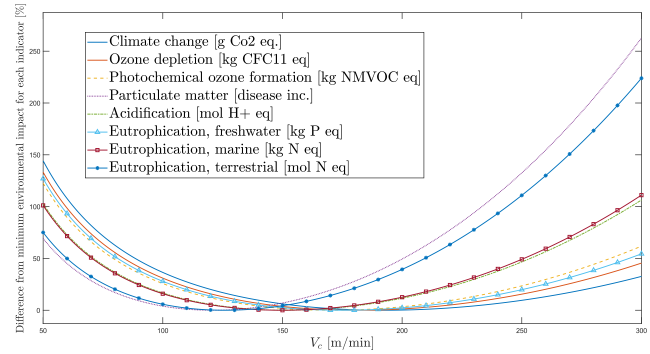


**Fig. 6.** Influence of cutting speed on the environmental indicators.

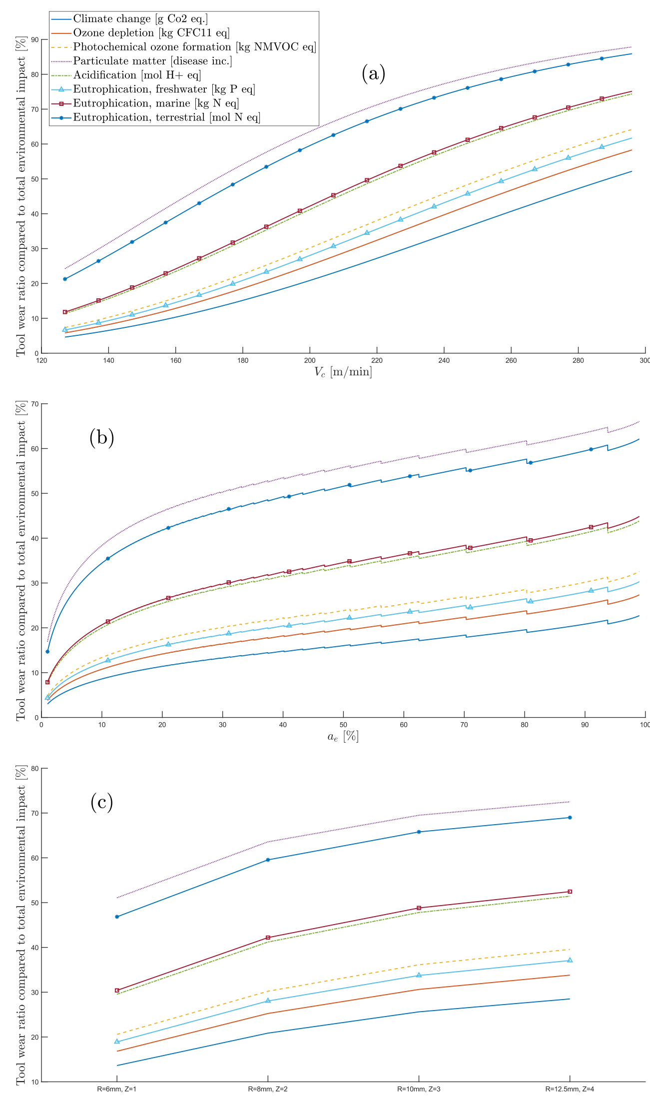


**Fig. 7.** Relative contribution of tool wear to the overall environmental impact for different cutting conditions: (a) Cutting Speed; (b) Radial depth of cut; (c) Cutting tool properties.

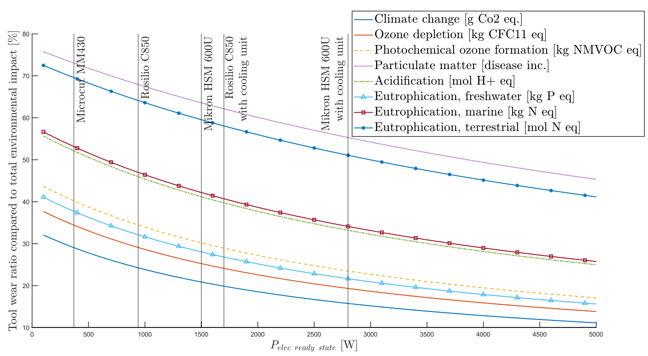


**Fig. 8.** Sensitivity analysis of no-load machine-tool power during steady state.

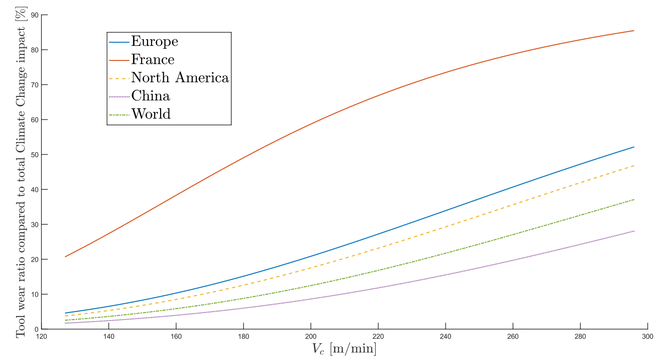


**Fig. 9.** Influence of geographical area on the environmental impact ratio.

The geometrical properties of the cutting tool (Fig. 7.c) modify the machining parameters. Increasing the tool radius reduces the number of side passes, and lowers the spindle speed for a given cutting speed. This leads to a reduction in electrical energy consumption compared to tool wear, which remains equivalent. Increasing the number of teeth means proportionally increasing the overall feed rate of the tool, which proportionally divides machining time and therefore reduces the associated electrical energy consumption. Overall, higher cutting conditions or tool radius/number of teeth tend to increase the dominance of tool wear in the environmental impact ratio. Indeed, tool wear is accelerated while machining time, the main parameter impacting electrical energy consumption, is reduced.

#### 4.5.4. Influence of machine tool no-load consumption

The no-load power of the machine-tools used and the associated no-load spindle power has a significant influence on the overall power consumption of the machining process. High no-load power leads to wasteful energy consumption during machining, thus increasing operating costs. The machine-tool no-load power is closely linked to the spindle power capacity, so it is important to choose the right machine tool for the intended machining operation. As the machine tool no-load power has a major influence on power consumption, the choice of machine-tool used strongly influences the electrical consumption/tool wear ratio of the machining operation (Fig. 8).

#### 4.5.5. Influence of the geographical area

The geographical area of our study has a significant impact on the results. Depending on where the machining is performed, the electrical energy consumed has a radically different environmental impact. For the proposed European scenario, the share of tool consumption for the Climate Change indicator was 22.8% for T2. In comparison, for a global energy mix, the share of other consumables decreases to 13.8%, while for a French energy mix it rises to 61.4%. Fig. 9 summarizes the evolution of the electricity/tool wear ratio as a function of cutting speed $V_c$ for different energy mixes. The evolution of the ratio is equivalent to that shown in Fig. 7.a. When moving towards higher tool wear in the overall environmental impact ratio across different geographical areas, it indicates that the production of electrical energy is greener according to the environmental indicator considered (Climate Change in Fig. 9). The environmental impact ratio can vary significantly depending on the geographical area, but is highly contingent on the specific environmental impact considered. The energy mix is therefore a determining factor in characterizing the environmental impact of machining processes.

Another aspect depending on the geographical area which can be important is transport. The associated impact is quantified by the mass transported (in tkm). As the ratio of environmental impact per unit mass of consumables is very high, the proportion of the impact of transport for the study is minimal.

## 5. Conclusions

This study has demonstrated its innovative nature by applying the LCA methodology to assess the environmental impact of machining process. Contrary to what is claimed by several studies in the literature, the consumption of electrical energy does not represent the totality of the machining environmental impact compared to the cutting tool consumption. The sensitivity analysis has highlighted the importance of considering various parameters that may have a significant impact on the relative contribution of consumables to the overall environmental impact, such as cutting speed, cutting tool or energy mix.

This methodology introduces a predictive model, innovatively designed to assess environmental impact and identifies the nature of consumption. Its innovative feature lies in its simplicity and ease of application. The methodology stands out for its universal applicability, allowing for predictions across diverse scenarios and industries. Its analytical model ensures ease of implementation compared to more complex finite element methods, streamlining the integration process into industrial practices. The inherent modularity allows for adaptability to various materials, tools, machine tools, or processes, catering to diverse applications within the industry. Notably, the methodology's capability for precise mono-criterion optimization makes it a versatile tool. While primarily designed for targeted environmental impact assessments, its flexibility extends to economic optimization, offering industries a comprehensive decision-making tool for sustainability considerations. The practical application of this method within an industrial organization can be smoothly orchestrated due to its adaptive characteristics. Sensitizing operators to the environmental aspects of machining, with an emphasis on understanding the analytical model and specific parameters considered, could lead to the incorporation of this method into decision-making processes.

The results have significant implications for future LCA studies in the field of dry machining, providing a more accurate assessment of the process impact compared to standard data in Ecoinvent. However, there were some limitations due to lack of data such as measurements of cutting tool production sites being confidential. This could affect the overall accuracy of the results, without being able to predict the influence of an input data modification on the results.

Future work should focus on addressing the gaps in data, by measuring and analyzing industrial consumables to refine inputs and reduce associated uncertainties. Refining the methodologies used will ensure that upcoming machining LCA studies are more effective. The analytical model provided offers a starting point for considering optimization in dry machining processes. However, optimizing machining operations is a multi-objective task due to the diverse set of environmental indicators involved. Quantitatively comparing these indicators becomes challenging as they are inherently incomparable. Future work should address the need to prioritize and compare environmental indicators in order to achieve overall optimization of machining.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jmapro.2024.02.063.

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