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Evaluation of Sustainability and Cost Effectiveness of Using LCO_2 as Cutting Fluid in Industrial Hard-Turning Installations

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Abstract: Conventional oil-based emulsions used in hard-turning processes present significant environmental and economic challenges, including high waste generation and hazardous disposal requirements. In response, cryogenic CO_2 cooling has gained attention as a sustainable alternative, offering improved productivity, reduced tool wear and a diminished environmental footprint. While technical advances have been reported, the industrial adoption of cryogenic cooling is still limited due to the lack of clear data on its actual viability. This paper moves beyond the analysis of the technical performance of cryogenic CO_2 cooling analyzed in previous works to conduct a detailed evaluation of its environmental and economic performance when machining roller bearing components with pCBN tools on a hard-turning installation. Utilizing Life Cycle Assessment (LCA) and Return-on-Investment (ROI) methodologies, this study compares cryogenic CO_2 with traditional cooling methods, quantitatively assessing the environmental impact and economic viability across different manufacturing scenarios. The findings reveal that cryogenic cooling can outperform conventional cooling regarding both environmental impact and cost-effectiveness thanks to the tool life improvements provided by cryogenic cooling, specifically in cases where high tool consumption is generated during hard-turning operations. These results provide critical insights for selecting cooling strategies during the design phase of industrial turnkey projects, highlighting the potential of cryogenic CO_2 as a superior solution for sustainable and efficient hard-turning operations.

Keywords: cryogenic machining; life cycle assessment; return on investment

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1. Introduction

The global manufacturing industry is increasingly driven by the dual imperatives of heightened competitiveness and sustainability. To boost sustainable consumption and production practices, environmental impact metrics associated with manufactured products are being demanded to support decision-making processes. Still, as businesses strive to meet the demands of a rapidly evolving marketplace, there is a pressing need to enhance operational flexibility, productivity and cost-effectiveness, limiting the effort towards minimizing environmental impact and quantifying metrics related to it. In this context, hard turning has emerged as a promising alternative to traditional, costly and cutting fluid-intensive grinding processes for the production of high-performance components [1,2]. This shift is crucial for industries such as automotive, railway, energy generation or industrial equipment industries, where precision and surface integrity are paramount.

Despite its advantages, challenges associated with the hard-turning process have hindered its widespread industrial adoption. The high thermal loads generated during machining lead to the rapid tool wear of expensive polycrystalline cubic boron nitride (pCBN) cutting tools, significantly increasing production costs [3]. Moreover, the deterioration of cutting tools adversely affects the surface integrity of machined parts. Due to the high operational loads that bearing components withstand, such surface alterations can create defects that compromise their performance and reliability [4,5]. As a result, manufacturers face the dual challenge of optimizing tool life while ensuring the quality of the finished product.

To address these challenges, effective heat removal from the cutting zone is crucial for improving both tool longevity and overall process performance. Traditionally, mineral oil emulsions have been employed for this purpose, but these fluids pose significant environmental and health hazards due to their chemical composition and disposal requirements. Furthermore, the reliance on such cutting fluids conflicts with the growing emphasis on sustainable manufacturing practices [6–8]. This has prompted a search for environmentally friendly alternatives to traditional metalworking fluids, with cryogenic cooling techniques emerging as a viable and promising solution. Cryogenic cooling involves the use of cryogenic liquids, such as liquid carbon dioxide (LCO_2) or nitrogen (LN2), to dissipate heat during machining. Additionally, the use of cryogenic cutting fluids can provide a feasible and sustainable technical solution to improve the performance during the machining of magnesium-based lightweight alloys, where water-based coolants should not be used due to the high reactivity and even the generation of highly explosive hydrogen gas [9]. Numerous studies have highlighted the benefits of implementing cryogenic cooling in hard-turning operations of bearing steels [10]. For instance, significant tool life increases were reported for pCBN tools when hard turning bearing steel using cryogenic cooling compared to conventional flooding and dry methods [11–13]. Besides tool behavior, improvements in machined surface integrity associated with cryogenic cooling have been documented. Both surface-generated residual stresses [11–17] and microstructure modifications [13–19] were analyzed in the literature, even reporting improvements in the corrosion resistance of the machined surfaces when using cryogenic cooling [17].

While the technical improvements provided by cryogenic cooling are extensively analyzed in research cited in the bibliography, the evaluation of the environmental impact and costs associated with cryogenic fluid use in the hard turning of bearing steel parts is limited in the existing literature. Reference [20] provides an analysis of the LN2-assisted hard turning of AISI 52100 using both ceramic and pCBN inserts. While this is a valuable contribution, there are notable limitations that should be addressed to enhance the applicability of the results. For instance, the analysis does not account for the embodied energy of the LN2 used, a factor crucial for a comprehensive environmental impact assessment. The exclusion of the carbon footprint associated with the production of cryogenic fluids such as LN2 and LCO_2 is a common issue in the literature [21], which can significantly affect the accuracy of the environmental burden calculations.

Additionally, as previously discussed, one of the primary technological benefits of using cryogenic cutting fluids is the reduction in tool wear. This improvement has a direct impact on the efficiency of hard-turning operations, leading to reduced costs and environmental impacts from tool usage. Thus, it is important that these factors are adequately reflected in the analysis. In [20], however, the environmental impact data for ceramic and pCBN tools are based on outdated sources related to tungsten carbide tools [22], which raises concerns about the relevance and accuracy of the results.

As global markets evolve towards sustainable consumption practices, metrics on the environmental impact of products are required to promote informed decision making beyond mere costs. Moreover, the industrial adoption of cryogenic cooling techniques towards sustainable production practices demands rigorous, performance-based calculations that can provide accurate quantitative assessments in comparison to conventional cooling systems. To meet these demands, investments in manufacturing systems increasingly hinge on the ability of turn-key solution developers to deliver traceable metrics related to the cost-effectiveness, productivity and environmental impact of their systems. In this sense, rigorous calculations related to productivity, costs and environmental impact are required during the design phase of industrial turn-key solutions.

This paper addresses these needs by evaluating the environmental and economic viability of hard-turning turn-key systems through the application of Life Cycle Assessment (LCA) and Return-on-Investment (ROI) calculations to obtain results across different manufacturing scenarios. The effect of using different cutting fluids on the environmental impact is quantitatively evaluated through the calculation of different impact indicators, while the cost-effectiveness is assessed through the estimation of the part cost and years for the amortization of the investment on an industrial turn-key installation. The work draws on data obtained in a previous study by the authors regarding the hard turning of AISI 52100 bearing steel with 65 HRC hardness using pCBN tools with different cryogenic and conventional cooling methods [13]. There, tool life and surface roughness improvements were reported when using LCO_2 as a cutting fluid. The present study evaluates the capability of such technical advancements to promote cryogenic cooling as an industrially viable sustainable manufacturing practice.

Findings suggest that LCO_2-assisted hard turning can improve both cost-effectiveness and environmental performance compared to conventional cooling methods, mainly in manufacturing scenarios where the hard-turning process generates high tool consumption. By thoroughly examining these aspects, this paper aims to contribute valuable insights to the ongoing discussion on sustainable manufacturing practices and highlight the potential of cryogenic machining as a key player in shaping the future of the industry.

2. Materials and Methods

2.1. Test Cases for Roller Bearing Component Manufacturing

In order to evaluate the proposed calculations for their application in the design phase of industrial turn-key solutions for hard turning of bearing steel components, two test cases representative of actual components for roller bearings are defined. They are selected to cover the span of different parts considered in the design of actual industrial turn-key installations, trying to avoid proprietary issues. The first part is a big-sized part with high cost and reduced yearly throughput. The second one, on the contrary, is a smaller part with high production requirements by year and low added value. Both parts show a similar simplified cylindrical geometry and include, as the main quality requirement, a mean surface roughness (Ra) value on the outer diameter of 0.2 μm. The schematic geometry for the test cases can be seen depicted in Figure 1, while Table 1 shows the yearly production and part purchase value for both the test cases defined.

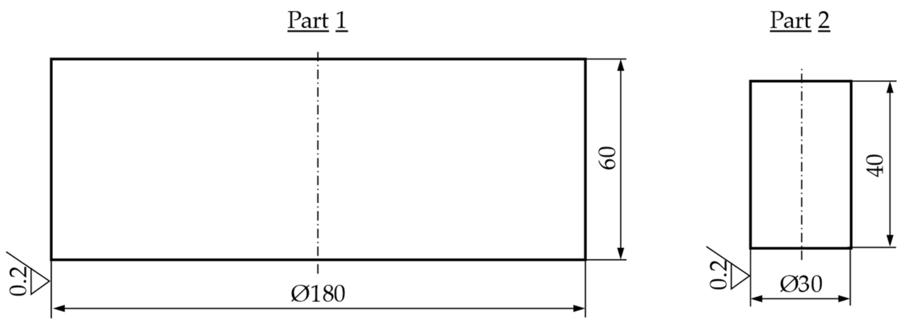

Figure 1. Geometry of the test cases analyzed.

Table 1. Manufacturing scenario for both test cases.

Condition	Part 1	Part 2
Yearly production—Parts	30,000	120,000
Part purchase value—EUR	20	3.5

2.2. Materials and Experimental Process Performance Data

As previously stated, the calculations in the present paper will be based on the experimental results obtained by the authors in a previous study [13]. There, hard-turning tests were conducted with DNGA 150608 NC4 BNC200 pCBN tools from Sumitomo (Sumitomo Electric Hardmetal Corporation, Itami, Japan) on actual bearing rings IR50X58X40-XL from Schaeffler (Schaeffler AG, Herzogenaurach, Germany) made of AISI 52100 bearing steel with 65 HRC hardness. Tool life tests were conducted using different cutting fluids, obtaining the evolution of the tool wear (VB) and generated surface roughness (Ra, Rz) along the execution of the tests.

During this study, it was observed that the use of oil emulsion as a cutting fluid would hinder the generated surface roughness on the parts, making it unfeasible to generate surface finishes below 0.25 µm in a robust manner. Thus, the present work focuses on the use of blown compressed air at 7 bar and liquid CO_2 in cannisters from Linde (Linde Gas, Pullach, Germany). The cryogenic-assisted hard-turning tests were conducted using a stable LCO_2 mass flow of 0.5 kg/min, delivered by an in-house-developed system [13].

Table 2 shows the cutting conditions employed to achieve a surface roughness Ra of 0.2 µm employing both blown air and LCO_2, together with the resulting tool life obtained for each cutting fluid. The tool life in Table 2 indicates the achievable cutting length (in meters) before the surface roughness gets below 0.2 µm due to the tool wear. As it can be seen, when using blown air, up to 4000 m of machining length can be obtained with the quality requirement defined for the surface roughness. When using LCO_2, thanks to the reductions in tool wear generated by cryogenic cooling, a longer machining length of 7000 m can be achieved while generating a surface roughness Ra below 0.2 µm. Considering the cutting speed employed during the tests (200 m/min), such values can be translated to 35 and 20 cutting minutes of cutting tool life for LCO_2 and blown air, respectively.

Table 2. Process performance data using LCO_2 and blown air as cutting fluids [13].

Cutting Fluid	Vc—m/min	fv—mm/v	ap—mm	Tool Life—m	Tool Life—min
LCO_2	200	0.05	0.1	7000	35
Blown Air	200	0.05	0.1	4000	20

2.3. Life Cycle Assessment—LCA Calculation Method

The present study intends to provide a method for the comparative evaluation of different cutting fluids in the design phase of hard-turning turn-key solutions. When making the calculation of turn-key solutions, the calculations for costs and cycle time are performed for one manufactured part. Following this, the Functional Unit for the LCA would also be the manufactured part. Moreover, the present study proposes a gate-to-gate LCA calculation to identify the differential environmental burden generated on the part by using different cutting fluids. Thus, the environmental impact generated by the equipment (hard-turning machines, peripherics, . . .) would not be included in the LCA as it would be the same for the different cases analyzed, nor would the material of the parts be included, as it is also the same. Thus, the LCA will cover the impact from the consumables (fluids, tools) and the energy consumption during hard turning to manufacture the part defined as the Functional Unit.

Regarding the impact categories covered by the LCA, in [20], only equivalent CO_2 emissions were accounted for. While this indicator is indeed important when calculating the environmental burden of a manufacturing process, other issues should be addressed too. Following the study proposed in [23,24] for the evaluation of the manufacturing and use of cutting tools, the LCA performed in the present study will cover the next impact categories: global warming potential [kg CO_2 eq], acidification potential [kg SO_2 eq], eutrophication potential [kg P eq], ozone depletion potential [kg CFC-11 eq], net water depletion [m^3] and smog potential [kg NMVOC eq]. The quantification for the environmental impact indicators related to the electrical energy and consumables employed for the LCA calculations can be seen in Table 3.

Next, the quantification for the indicators above is detailed for the different process input flows covered by the gate-to-gate LCA.

Table 3. Summary of the Life Cycle Inventory.

Impact Indicator	1 kWh	Tool Tip	1 kg LCO_2	1 L/min Air x min
Global warming potential [kg CO_2 eq]	2.48×10^{-1}	7.30×10^{-1}	8.94×10^{-2}	4.59×10^{-5}
Acidification [kg SO_2 eq]	3.56×10^{-1}	3.15×10^{-3}	1.28×10^{-4}	6.59×10^{-8}
Freshwater eutrophication [Kg Peq]	8.07×10^{-5}	4.15×10^{-3}	2.91×10^{-5}	1.49×10^{-8}
Water depletion [m^3]	5.77×10^{-2}	1.55×10^{-1}	2.08×10^{-2}	1.07×10^{-5}
Ozone depletion [kg CFC-11 eq]	1.72×10^{-8}	5.87×10^{-8}	6.19×10^{-9}	3.18×10^{-12}
Photochemical oxidant formation [kg NMVOC eq]	2.70×10^{-4}	1.36×10^{-3}	9.76×10^{-5}	5.00×10^{-8}

2.3.1. Electrical Energy

To quantify the impact of the electrical energy consumption, the environmental impact from different electricity generation technologies per generated kWh was evaluated. In 2022, the United Nations Economic Commission for Europe published a comprehensive report with the categorization of energy technologies and their environmental impact for the Life Cycle Assessment of different electricity sources [25]. There, a detailed identification of the environmental impact of different energy generation sources in the EU region (EU28) can be found. To account for the different technologies actually employed for electrical power generation, information published by the European Council based on the Eurostat Dataset for the electricity generation technology mix in 2022 [26] was employed in the present study. The quantification for each impact indicator of the environmental impact induced by the generation of 1 kWh of electricity can be seen in Table 3.

2.3.2. Cutting Tools

Due to the improvement in tool life generated using cryogenic cutting fluids in comparison to blown air (Table 1), the differential burden generated on the parts by the lower tool consumption is addressed by the proposed LCA. The impact from the cutting tools included both the cemented tungsten carbide body and the pCBN tips from the inserts used during the cutting process. The mass of the cemented tungsten carbide body of the cutting inserts was calculated to be 16.02 g, so a fourth of that mass was included in each calculation, and its environmental burden was obtained based on the data provided by [23] for the manufacturing of cemented tungsten carbide in Europe. It should be noted that the cutting inserts used had 4 cutting tips, so the tungsten carbide mass on the whole insert was divided by 4 to evaluate its impact on each cutting tip.

Regarding the pCBN tool tip, its mass was calculated to be 0.08 gr. Its environmental burden was calculated starting by the generation of CBN granulates. In [27], the high energy consumption during the CBN synthesis was identified as the main source of the environmental impact of the granulate generation process, providing the quantification of 2.19 kWh per CBN gram. After the CBN granulates were obtained, they were processed by a High-Pressure High-Temperature (HPHT) sintering process to produce pCBN disks and then cut by WEDM to generate the final tool tip which was welded to the tungsten carbide body. While no data were found to be available for this process on pCBN, the analogous process for PCD was analyzed by [24], obtaining the value of 2.5 kWh per tool tip. This way, considering 0.08 gr of pCBN for a tool tip, 2.675 kWh energy consumption was calculated for the manufacturing of each pCBN tip. The quantification for each environmental impact indicator associated with 1 tool tip (covering both the tungsten carbide body and the pCBN tool tip) can be seen in Table 3.

2.3.3. Cutting Fluids

As stated in the introductory section, the LCA of cryogenic-assisted machining processes should account for the environmental burden associated with the capture and liquefaction of cryogenic fluids like LN2 and LCO_2. Indeed, even though Carbon Capture and Storage or Utilization (CCS/CCU) technologies have significantly improved in the last decade due to the need to meet the decarbonization targets defined as a result of the Paris

Agreement to limit the global temperature increase, their electrical energy consumption is still significantly high [28]. In [29], the energy requirements for the liquefaction of 1 ton of CO_2 generated as a by-product from the ammonia synthesis was employed for the quantification of the environmental impact of providing LCO_2 as an industrial feedstock, obtaining the value of 120 kWh for the liquefaction of 1 ton of LCO_2. Besides employing such a value as the energy burden for the LCO_2 used during LCO_2-assisted machining, the present study considered the power consumption from the LCO_2 delivery system too. Such consumption was measured to be 1.37 kW during the cutting tests when providing a stable 0.5 L/min LCO_2 mass flow.

The present study evaluates the use of LCO_2 as a cutting fluid in comparison to blown air. Such blown air was provided at 7 bar pressure by a standard air compressor of 22 kW power and a maximum capacity of 3800 L/min. The blown air flow employed during the tests was measured with a pneumatic flow meter to be 50 L/min. This way, the electrical power associated with the blown air was quantified in 0.005 kW during the execution of the cutting tests. These power values were used to quantify the values taken by the impact indicators during the tests based on the electrical energy consumption and the process duration (Table 2).

2.3.4. Cutting Process

The use of cryogenic fluids can have a significant effect on the cutting forces and, this way, the power consumption during cryogenic-assisted machining processes in comparison to conventional cooling techniques [6,7]. To account for this differential power consumption, the cutting power was obtained through the TRACE function of the Siemens Sinumeric 840D CNC device during the execution of the cutting tests. The values obtained were 580 kW when using LCO_2 during the cutting tests and 575 kW for the use of blown air.

Such an increase in the cutting power can be associated with lower softening induced in the workpiece material when using cryogenic cooling. As in the case of the cutting fluids, the impact generated by the cutting process during the test execution was based on the identified power values and process duration.

2.4. Cost and Return on Investment—ROI Calculation Method

As stated in the introduction to Section 2, the present study focuses on the evaluation of the costs and Return on Investment for a hard-turning installation. Thus, the ROI calculation was founded on the detailed calculation of the final part cost for the test cases defined in Section 2.1. To do so, the costs associated with the equipment, consumables, electrical energy consumption and hourly labor were considered in the present study. Table 4 shows the values for all the costs considered in the study in a summarized manner, while the next lines describe the sources for such data.

Table 4. Values employed for the turn-key installation costs during the ROI calculations.

Item	Cost (EUR)
Hard-turning machine	500,000
LCO_2 equipment	40,000
Tool tip	20
LCO_2 liter	1.5
Hourly labor	35.6
1 kWh energy	0.2008

Regarding the equipment costs, taking into consideration the actual solutions provided by Danobat for hard-turning installations, an approximate value of EUR 500,000 was employed for a precision CNC hard-turning lathe. In the case of the cryogenic cooling delivery system, the LCO_2 system developed within [13] was quantified as EUR 40,000. It should be noted that the present study did not include the cost for the compressor employed for the delivery of the blown air, as it is standard equipment present in machining workshops and would not be directly related to the hard-turning turn-key installation.

Concerning the cost for the consumables employed during the hard-turning operations, the values employed here are the ones obtained by the authors from the providers when executing the tests described in [13]. The cost of the pCBN tool employed during the tests was roughly EUR 80, with 4 usable cutting tips, so each cutting tip was evaluated as costing EUR 20. In the case of the LCO_2 used as a cryogenic cutting fluid, the average cost for 1 L of LCO_2 during the test execution was EUR 1.5.

The costs associated with the electrical energy consumption employed during the calculations was 0.2008 EUR/KWh, a value published by Eurostat for the average price in the EU during the second half of 2023 for non-household consumers [30]. Finally, a value of EUR 35.6 was employed for the hourly labor costs, the average value in the EU in 2023 published by the Eurostat [31].

To evaluate the capability of the turn-key solutions to even the cost related to the equipment inversions and the manufacturing costs, the ROI calculations require for the quantification of the income to be generated by the turn-key installation during sequential years after the investment for the industrial equipment. This is based on the manufacturing costs associated with each part in comparison to the actual purchase value of each part in the market. To evaluate the manufacturing costs for each part, a working scenario with a total of 1700 work hours per year, 3 shifts and an Overall Equipment Effectiveness (OEE) of 85% was considered, including an equipment amortization timeline of 8 years. The processing times were calculated as 6.96 min and 0.93 min for parts 1 and 2, respectively. In the case of the non-productive times, 1 min for the part handling and 0.5 min for the tool change time were employed in the present study. Such values were employed for the estimation of the final part manufacturing costs and to obtain the ROI values from the installation 8 years after the investment is performed.

3. Results

Next, the LCA and ROI calculations proposed in Sections 2.3 and 2.4 were applied to the test cases introduced in Section 2.1. The calculations for both test cases were performed for the use of cryogenic LCO_2 and blown air as cutting fluids, considering a machining process comprising two machining passes. The input data employed for the cutting conditions and tool life for both cutting fluids are the data included in Table 2.

3.1. LCA Calculations

Figure 2 shows the results of the environmental impact generated during the manufacturing of one part for the different impact indicators obtained from the LCA analysis for the test case 1. For each indicator, the results from both cutting fluids are depicted, detailing the contribution from the tool usage, cutting process and cutting fluid application.

It should be noted that these results are obtained from the gate-to-gate LCA proposed in the present study to provide differential calculations for the comparative evaluation of using different cutting fluids. The environmental impact of manufacturing these parts would be significantly higher when performing a cradle-to-gate LCA for them.

As it can be seen, when using blown air as a cutting fluid, for all the impact indicators evaluated, the main environmental impact contributors are the cutting tools, while the contribution from the cutting process and the application of the cutting fluid is residual. In the case of using LCO_2, instead, the tool life improvement generated reduces the impact from the cutting tools by more than 50%. However, the impact from the cutting fluid is greatly increased due to the energy burden of the LCO_2. Nevertheless, in comparison to the use of blown air, the use of LCO_2 enables a reduction in the environmental impact generated during the manufacturing of test case 1 for all the impact indicators evaluated.

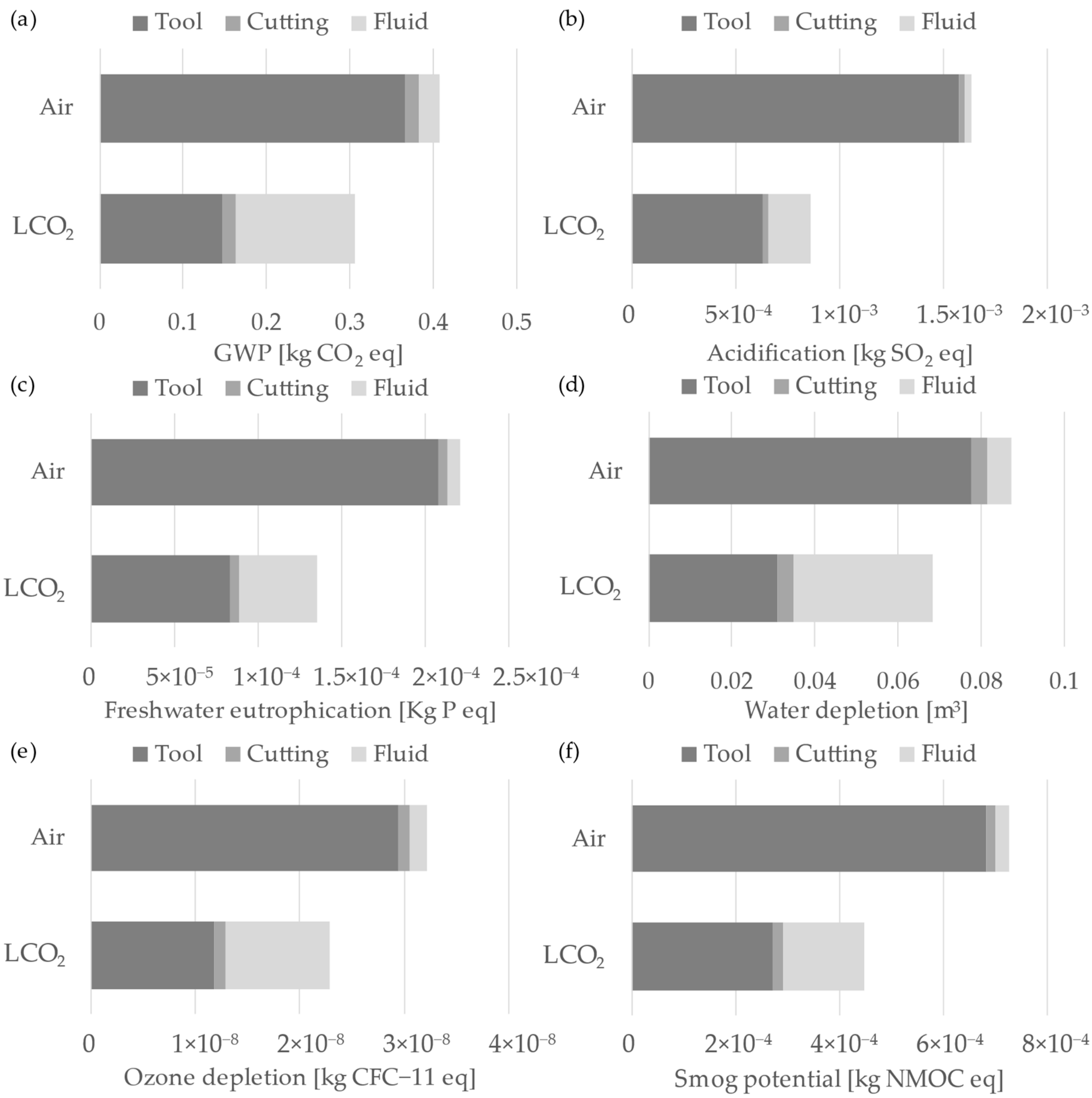

Figure 2. Environmental impact indicator values for test case 1 and both cutting fluids analyzed, (**a**) global warming potential [kg CO_2 eq], (**b**) acidification potential [kg SO_2 eq], (**c**) eutrophication potential [kg P eq], (**d**) ozone depletion potential [kg CFC-11 eq], (**e**) net water depletion [m^3] and (**f**) smog potential [kg NMVOC eq].

Next, the results from the LCA calculations obtained for test case 2 are described. Figure 3 shows the values obtained for the selected environmental impact indicators for manufacturing test case 2 with both blown air and LCO_2 as cutting fluids. The obtained results are depicted in an analogous manner to Figure 2, detailing the contribution from the tools, cutting process and cutting fluids. As in the case of test case 1, when using blown air as a cutting fluid, the main impact generator for all the environmental impact indicators is again the cutting tool, while the relative contribution from the cutting process and the fluid is slightly increased in comparison to test case 1.

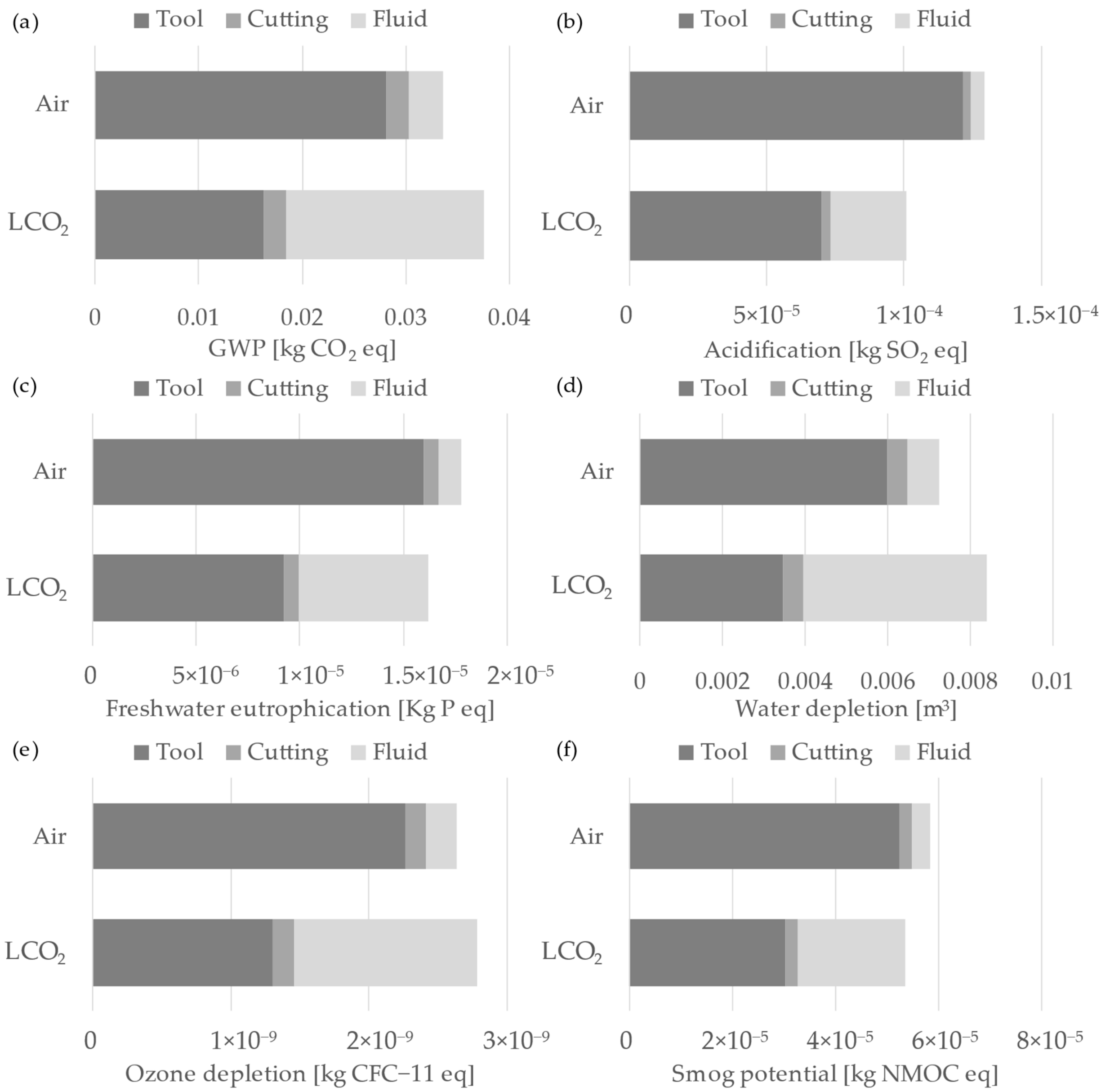

Figure 3. Environmental impact indicator values for test case 2 and both cutting fluids analyzed, (**a**) global warming potential [kg CO_2 eq], (**b**) acidification potential [kg SO_2 eq], (**c**) eutrophication potential [kg P eq], (**d**) ozone depletion potential [kg CFC-11 eq], (**e**) net water depletion [m^3] and (**f**) smog potential [kg NMVOC eq].

When using LCO_2 as the cutting fluid, the environmental impact contribution from the tool gets reduced, as in the case of test case 1, thanks to improvements in the tool performance in comparison to blown air. However, the relative reduction generated by using LCO_2 is significantly lower than that obtained for test case 1 for all the indicators analyzed. Moreover, the relative contribution of the LCO_2 to the environmental impact from manufacturing test case 2 is greatly increased in comparison to the results obtained for test case 1 for all the impact indicators analyzed. This increase is such that using LCO_2 as a cutting fluid generates a higher impact than the use of blown air for the indicators related to global warming potential, water depletion and ozone depletion potential.

3.2. Cost and ROI Calculations

Concerning the cost and ROI calculations, Figure 4 displays the part cost calculations for test case 1 for both cutting fluids considered. The part cost shows the contribution from the different items indicated in Section 2.3: equipment amortization, hourly labor costs, tool costs and operational energy costs. In the case of the use of LCO_2, the cost associated with this consumable is added too. The percentual contribution for each of these items in the final part cost can be seen in Figure 5.

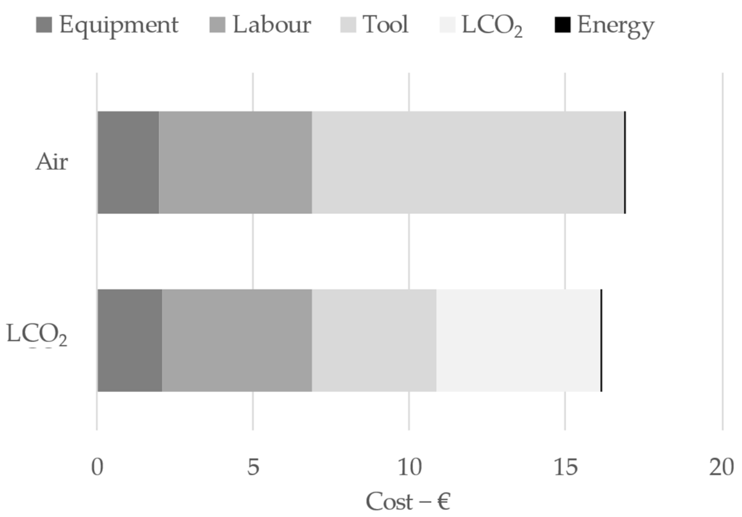

Figure 4. Part cost calculations for test case 1 for both cutting fluids considered.

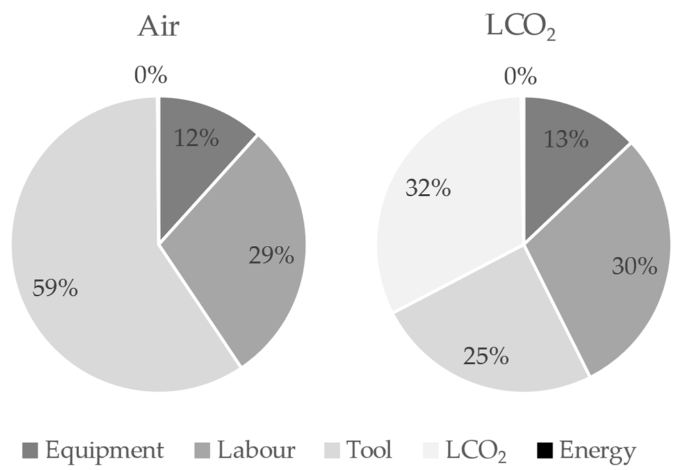

Figure 5. Percentual allocation for each cost item in the overall part cost for both cutting fluids.

As it can be seen, the costs associated with equipment, labor and energy consumption are very similar for both cutting fluids employed. For both cases, the cost related to energy consumption is negligible. In the case of using blown air as cutting fluid, the tool costs are the predominant cost contribution, with more than 50% of the part cost coming from this item. When using LCO_2 as a cutting fluid, due to the tool life improvements generated, a significant reduction in the cost related to the cutting tool can be seen. Nevertheless, the LCO_2 as a consumable becomes the highest cost contributor (32%) in the final part cost. Still, the use of LCO_2 as a cutting fluid results in a lower overall part cost (EUR 16.15) in comparison to the use of blown air (EUR 16.87).

Based on the part manufacturing costs, ROI calculations were performed using the yearly production values indicated in Table 1. Following the defined amortization timeline, these calculations were performed for 8 years after the industrial investment. The obtained ROI results can be seen in Table 5. As it can be seen, for the manufacturing scenario defined within the present study, the use of both cutting fluids would generate positive ROI values before the amortization timeline. Thanks to the lower part cost generated when using LCO_2, an installation with LCO_2 would yield a faster ROI in comparison to blown air, obtaining positive values in the fifth year, while the installation using blown air would require an additional year. Following this progression, the return from the installation after the amortization timeline would also be higher when using LCO_2.

Table 5. ROI values for installation manufacturing test case 1 for both cutting fluids considered.

Years After Investment	Return on Investment—EUR, k	
	LCO_2	**Air**
1	−424.37	−406.02
2	−308.74	−312.04
3	−193.11	−218.06
4	−77.48	−124.09
5	38.15	−30.11
6	153.78	63.87
7	269.42	157.85
8	385.05	251.83

Regarding the results for test case 2, Figure 6 shows the values obtained for the part manufacturing costs. As in the case of Figure 4, the contribution from equipment, tool, labor, energy consumption and cutting fluid is detailed for both the cutting fluids analyzed. The percentual contribution from each of these items to the total part manufacturing cost can be seen in Figure 7. As it can be seen, the cost related to energy consumption is negligible for both cases. The main cost contributor for the use of blown air is the labor costs, with a percentual share of 48% of the total costs (Figure 7). While in the case of test case 1, the tool costs are the predominant cost contributor, in the case of test case 2, due to its lower size and lead time, the relative tool costs are significantly reduced to second place, with a 32% share of the total costs.

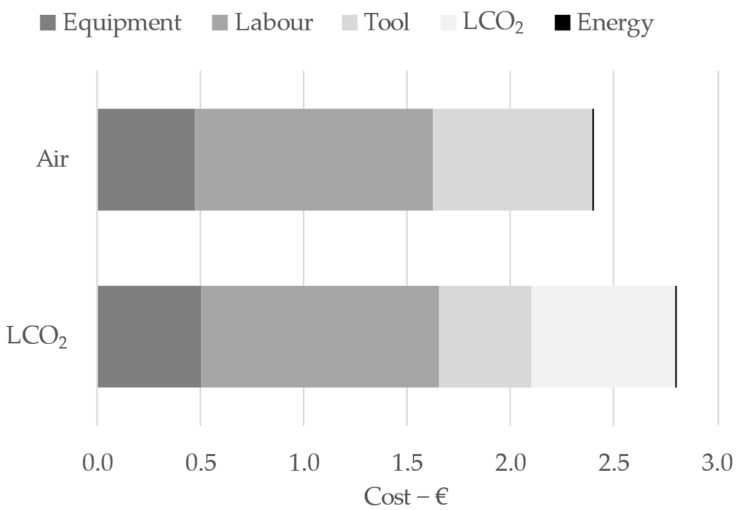

Figure 6. Part cost calculations for test case 2 for both cutting fluids considered.

Thus, in the context of a small part with high throughput, most of the part costs are related to labor, and the relative tool cost reductions generated by using LCO_2 as a cutting fluid show a limited effect on the overall part cost. When using LCO_2, the labor costs are still the predominant contributor (41%), with the cost share from the tool reduced to 16%. However, the cost associated with the LCO_2 surpasses the generated tool cost reductions due to a higher tool life and, therefore, the final part manufacturing cost using LCO_2 (EUR 2.8) is higher than when using blown air (EUR 2.4).

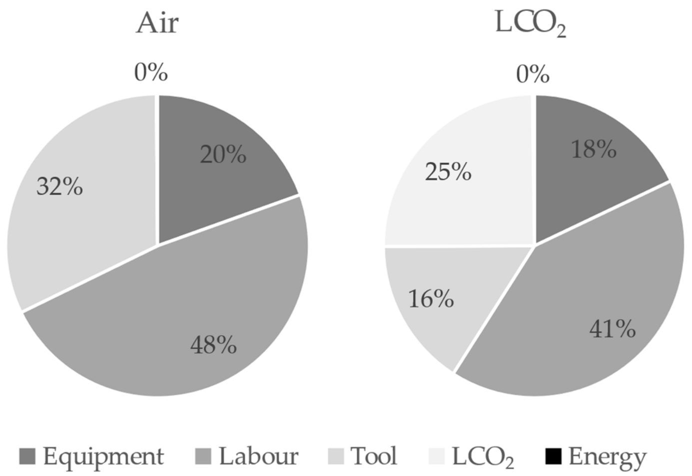

Figure 7. Percentual allocation for each cost item in the overall part cost for both cutting fluids.

After obtaining the part manufacturing costs for test case 2, the ROI calculations were performed in an analogous manner to that described for test case 1, using an amortization timeline of 8 years after the investment in the hard-turning installation. Table 6 shows the obtained ROI results for test case 2 when using both LCO_2 and blown air.

Table 6. ROI values for installation manufacturing test case 2 for both cutting fluids considered.

Years After Investment	Return on Investment—EUR, k	
	LCO_2	**Air**
1	−456.07	−367.44
2	−372.14	−234.88
3	−288.21	−102.32
4	−204.28	30.24
5	−120.35	162.80
6	−36.42	295.36
7	47.51	427.92
8	131.43	560.48

As in the case of test case 1, hard-turning installations using either blown air or LCO_2 as cutting fluids would yield positive results before the amortization timeline. However, since the use of blown air would yield a lower part manufacturing cost, an installation with this cutting fluid would obtain a faster ROI, generating positive values in the fourth year after the investment. In the case of an installation using LCO_2, it would require 3 additional years to yield positive results.

4. Discussion

This work presents a framework for the quantitative evaluation of the sustainability and cost-effectiveness of LCO_2-assisted hard-turning installations during the design phase. By detailing the application of Life Cycle Assessment (LCA), cost analysis and Return-on-Investment (ROI) calculations, the framework is tested on two case studies representing typical industrial parts suited for hard-turning turn-key installations.

The results confirm the initial considerations related to the importance of incorporating both cutting fluids and tools into the LCA and cost assessments. On the one hand, the reductions in tool wear generated by using LCO_2 as a cutting fluid instead of blown air have a direct effect on the environmental impact and costs associated with the tool consumption in hard-turning installations. On the other hand, the opposite is observed for the consideration of LCO_2 as a consumable, as the environmental burden and cost associated with it are higher than those for the blown air. Similar cost and environmental impact reductions associated with tool life improvements were reported in reference [20] when hard turning bearing steel with liquid nitrogen as a cutting fluid. However, the environmental burden of the cryogenic fluid was not accounted for, so the impact from this consumable on the obtained results is not analyzed. Both these effects can be quantitatively evaluated through the proposed evaluation framework, and the result will indicate whether using LCO_2 will outperform conventional cooling or not.

The present analysis showcases that the use of LCO_2 as a cutting fluid in hard-turning installations can be beneficial, both in terms of sustainability and cost-effectiveness, depending on the manufacturing scenario. In cases where small parts with high throughput are produced, such as in test case 2, tool consumption per part is low, limiting the environmental and economic impact of tool wear. Under these conditions, LCO_2 does not offer significant environmental or economic advantages. However, for larger parts with longer machining times and higher tool consumption, as seen in test case 1, the enhanced tool performance provided by LCO_2 proves advantageous. In such scenarios, the benefits of reduced tool wear can outweigh the environmental burden and cost associated with LCO_2, making it a sustainable and cost-effective solution for hard-turning applications.

It should be noted that the obtained results from both the LCA, part cost and ROI calculations are based on data obtained from a previous study by the authors [13]. The application of the data presented here should be limited to the part and tool materials, cutting conditions and cooling fluids employed here. Application beyond these parameters to other machining processes or materials should be carried out with caution. In addition, inevitably, some of the data employed here related to equipment and consumable costs from Table 4 can be outdated. In the same manner, environmental impact data (Table 3) for tools and cutting fluids could change as innovations are applied to the manufacturing processes and energy generation technologies employed for their production. Nevertheless, the proposed evaluation framework would still be valid regardless of changes in the values for the input parameters.

The industrial adoption of cryogenic cooling as a sustainable and cost-effective solution for machining operations depends on rigorous, performance-based calculations rather than the assumption that replacing conventional cutting fluids with cryogenic alternatives is inherently sustainable. The framework proposed in this paper, based on LCA and ROI analyses, provides a quantitative approach for assessing the viability of cryogenic fluids as a replacement for traditional cutting fluids in industrial turn-key installations, supporting the manufacturing industry's transition to more sustainable practices.

Furthermore, as policymakers and markets increasingly prioritize sustainability, environmental impact metrics can become valuable indicators alongside the traditional monetary cost of components. The dual approach proposed here offers consumers and industries the data needed to support informed decisions and promote a broader shift toward sustainable consumption and production.

5. Conclusions

The following conclusions can be drawn from the obtained results:

- The environmental burden associated with both the tools and cryogenic fluids must be accounted for to properly evaluate the overall environmental impact of the cryogenic-assisted processes.
- The industrial viability of using cryogenic cutting fluids during hard-turning operations as a sustainable manufacturing practice relies on the cost and environmental impact reductions generated by improving the tool performance in comparison to conventional cutting fluids.
- Depending on the parts to be manufactured and the manufacturing scenario, the use of cryogenic LCO_2 can outperform conventional cutting fluids, both in sustainability and cost-effectiveness. As a rule of thumb, test cases with longer machining times and higher tool consumption will be more likely to generate better results with cryogenic fluids.

- The use of LCA and ROI calculations can provide performance-based metrics for the quantitative evaluation of the industrial viability of cryogenic cooling as a sustainable and cost-effective solution.
- Quantitative metrics like the ones proposed here can enable the rigorous evaluation of manufacturing processes and products, supporting informed decisions and encouraging sustainable consumption and production practices.

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