An Introduction to the Use of Life Cycle Assessment in Machining

Diego Carou, Jose Adolfo Lozano, Fernando León-Mateos, Antonio Sartal, and Munish Kumar Gupta

Abstract In today's globalized economy, growing concern exists regarding the tradeoff between economic growth and respect for the environment. This conflict is not alien to companies; as many have started to include environmental sustainability in addition to their usual objectives of profitability and efficiency. The manufacturing industry is a major contributor to the overexploitation of resources and to environmental pollution through the generation, accumulation or improper disposal of waste and greenhouse gas emissions. In this context, machining is one of the main processes in manufacturing. Its intrinsic characteristics make it an intensive process regarding energy, water consumption, and waste generation. In addition, cutting tools suffer from high wear rates that result in high tool consumption and, thus, a high environmental footprint. Life Cycle Assessment (LCA) is the most widely used methodology for assessing the environmental impacts of manufactured products. It has also been used in machining because it allows a holistic approach that encompasses all environmental exchanges of a product or process throughout its life cycle. Particularly, it allows comparing scenarios when a proper baseline is established to select more environmentally friendly ones. However, comparisons among setups that include, for instance, different workpiece materials are hardly helpful due to the influence of machinability on the process. The present study is aimed at introducing LCA into machining. It provides an overview of relevant studies in which the LCA framework was applied to machining and other manufacturing processes.

Keywords Energy · Raw materials · Life cycle assessment · LCA software · Machining · Sustainable manufacturing

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1 Introduction

In today's globalized economy, the conflict between economic growth and respect for the environment is becoming increasingly acute (Liu et al., 2018a). The levels of well-being achieved in developed countries have led to more significant social concern for environmental issues, which companies also have internalized. From the design of their products to their industrialization and distribution, companies modify their behaviors to comply with regulatory frameworks and to respond to consumers' new agile and "green" demands (Kaswan & Rathi, 2020; Ozcelik et al., 2021; Sartal et al., 2017).

Today, environmental sustainability is an imperative strategy for business organizations in this new context. It must be added to the usual profitability and efficiency objectives (Garza-Reyes, 2015; Sartal et al., 2017, 2022). The traditional assumption that natural resources are limitless and that the environment can compensate for all human actions is no longer acceptable (Garetti & Taisch, 2012). The rapid consumption of natural resources and the acknowledgment of human activity as the source of global warming have increasingly motivated firms to modify their strategies and develop cleaner manufacturing processes and services to be ecologically sustainable (Barreto et al., 2010). In light of this, the green paradigm has emerged. This philosophy aims to diminish or avoid all negative impacts of the firm's products and services on the environment. Moreover, it is linked to operations, with the objective being to improve environmental efficiency while also keeping the organization's traditional profitability goals intact (Garza-Reyes, 2015).

The manufacturing industry is of paramount importance within the industrial sector. According to the latest available data (2021), it is estimated that the manufacturing industry represents 17% of the gross domestic product (GDP) of national economies (World Bank, 2022) and 13.1% of world employment (ILOSTAT, 2020). As a result, manufacturing is the one of the major contributors to the overexploitation of resources (energy, raw materials and water), as well as to environmental pollution through the generation, accumulation or improper disposal of waste and greenhouse gas emissions (Álvarez et al., 2017; Goindi & Sarkar, 2017; Sun et al., 2019).

Many industries already evaluate their environmental footprint and have changed the guidelines of their production by considering strict norms and environmental regulations (Yıldırım et al., 2019). Therefore, the discussion on implementing sustainability strategies in manufacturing has become a trending research topic (Mia et al., 2019), with the objective being to increase the processes' efficiency while also increasing production rates (Gupta et al., 2016, 2020).

Machining is an essential manufacturing process (Aramcharoen & Mativenga, 2014; Pusavec & Kopac, 2009). Its intrinsic characteristics make it an intensive process with regard to energy and water consumption, as well as waste generation (Campatelli et al., 2014; Cao et al., 2012; Chen et al., 2015; Goindi & Sarkar, 2017; Wickramasinghe et al., 2020; Zhao et al., 2012). In addition, due to the severe conditions during material removal, cutting tools suffer from high wear rates that result in high tool consumption and, thus, high environmental costs.

All of the above mentioned circumstances show that machining processes generate relevant environmental impacts. Therefore, improving the sustainability of machining should be a clear objective for companies in their transitions from traditional production systems to sustainable ones. Various conventional sustainability assessment methods have been used, including mathematical modeling, life cycle assessment (LCA), empirical modeling, etc., to improve environmental performance. These methodologies allow for analyzing the results of a process in connection with environmental and machining aspects (Hegab et al., 2018a, 2018b; Mia et al., 2019; Singh et al., 2020).

The LCA methodology is the most widely used for analyzing the environmental impacts of manufactured products (García et al., 2014). Regarding machining, LCA is gaining attention as a method for evaluating a process's sustainability (Campitelli et al., 2019). This attention is probably given because LCA allows for a holistic approach that encompasses all of the environmental exchanges (emissions, energy, raw materials and waste) of a product or process throughout its life cycle (Campitelli et al., 2019; Filleti et al., 2017). In addition, it is a standardized technique (International Organization for Standardization, 2006a, 2006b), which may allow for comparisons between similar processes to select the most efficient use of resources and, therefore, the most environmentally friendly alternative.

In recent years, the use of LCA for assessing manufacturing processes has been implemented, and several related studies can be found in the literature. However, the need still exists for critical reviews that gather the developed knowledge and present to readers a comprehensive overview that shows the potential and limitations of the method.

Given the relevance that machining processes have in matters related to the environment, the present chapter focuses on the sustainability of the machining processes. Mainly aiming at developing a complete review of the recent work on LCA in machining and comparing it against other manufacturing processes. This review will allow readers to understand the current state and the challenges in the coming years. The chapter includes four sections after this introduction. Section 2 covers the main issues related to sustainability in machining. Section 3 briefly describes the LCA methodology. Section 4 discusses the application of LCA to machining and other alternative manufacturing processes. Section 5 presents some implications and insights. Finally, Section 6 summarizes the chapter's main conclusions.

2 Sustainability in Machining

Machining is one of the most extended manufacturing processes in the industry. It is a subtractive one, in which the final shape of a part is obtained by removing chips from a workpiece using sharp tools. Conventional machine tools, such as grinding, milling and turning machines, and modern flexible CNC centers are used to do the operations. The machine tools have evolved from traditional manual machines to modern CNC machines that offer users high precision and flexibility for producing intricate shapes.

Machining is a complex process that is highly demanding in terms of energy requirements and includes various inputs, such as cutting tools and cutting fluids. Cutting tools can be either solid tools or indexable tools made of a wide range of materials, which require proper tool holders. Cutting fluids, which generally use animal, mineral or vegetable oils mixed with water and other chemical compounds, are usually employed. The process can be arranged in multiple ways, including fixture settings, machining parameters, operations order, path strategies, etc. Regarding the outputs, machining produces a large quantity of chips, cutting fluids to be reused or disposed of, dust generated during cutting and gases produced through the vaporization of the cutting fluids. In Fig. 1, one can see the main inputs and outputs in machining involving both traditional and non-traditional processes, particularly those relevant to the environmental impact.

Based on Fig. 1, two approaches are open for researchers to improve the sustainability of the process. One is to evaluate a specific input or output to diminish or suppress the associated environmental impact, such as reducing energy consumption and, thus, atmospheric emissions. The second is integrating all inputs and outputs to perform a single evaluation. This strategy combines all accessible and relevant process information to assess its impact by incorporating the effects of inputs and outputs. Some authors propose using algorithms that allow for conveniently integrating the data. For instance, Hegab et al. (2018a) presented metrics for evaluating a process's sustainability. Other approaches can also be identified, such as incorporating the environmental point of view into the design process, which is eco-design (Favi et al., 2019; Züst et al., 2016). Another method is the Life Cycle Assessment (LCA), which will be reviewed in more detail in the following sections. Finally, some researchers, such as Tao et al. (2018), have proposed more integrated approaches for

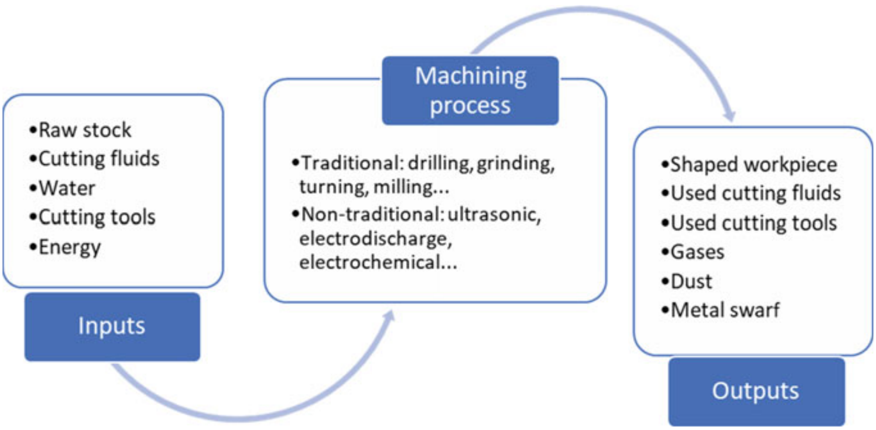

Fig. 1 Machining process: inputs and outputs

eco-design by integrating the modules of LCA, CAD/CAE and optimization to drive product design with a sustainable approach.

The inputs of the process can be differentiated into raw and intermediate materials, including the cutting fluids and water, workpiece materials, cutting tools, and energy (power consumption). The relevance of the inputs is clear by noting that most of the residues are generated directly from them, such as the cutting tools. Next, these sources are explained in more detail.

2.1 Raw Materials

Machining involves using raw materials, such as cutting tool and workpiece materials, as well as mineral or vegetable oils, which are usually mixed in water or gases. The influence of these materials on the environment should be conveniently analyzed. For a long-term analysis, even materials used for manufacturing the machine-tools should be considered input materials considering that they may be recovered, such as those used for structural uses (e.g., cast iron) (Cao et al., 2012).

The use of traditional cooling/refrigeration methods (i.e., flood cooling) based on mineral oils is identified as a harmful solution for human health and ecological systems (Wickramasinghe et al., 2020). Thus, in the last decades, efforts have been carried out to devise sustainable alternatives. These more recent strategies are helping to foster the development of greener processes and include, among others, dry machining, cryogenic machining and minimum quantity lubrication (Carou et al., 2016; Sarıkaya et al., 2016).

Benedicto et al. (2017) presented a comprehensive comparison of some of the main cooling/refrigeration alternatives based on their environmental impacts. They analyzed several dimensions: residue, fluid drag-out, dangerous substances, mist and emissions, and workers' health hazards. The methods were compared based on their relative costs and sustainability, with dry machining and gaseous cooling being the more sustainable solutions. In the review, dry machining was identified as the cheaper solution. However, despite the undoubted benefits of dry machining, it still finds problems for application when machining certain materials, for instance, due to the temperature increase in the cutting zone and tool (Goindi & Sarkar, 2017).

Water consumption is one of the major current concerns in terms of sustainability. Access to water is one of the Sustainable Development Goals of the United Nations (2022). The industry is one of the major consumers, and efforts are being made to reduce its water consumption. Zhao et al. (2012) presented a study on freshwater consumption in the drilling, milling and turning of medium carbon steel using the Unit Process Life Cycle Inventory (UPLCI) model. In the study, the direct water footprint is associated mainly with cutting fluid consumption and system maintenance. The indirect water footprint linked to energy consumption is related to electricity consumption. One of the major contributions of the study is the finding that the indirect water footprint is larger than the direct one is. Still, it notably depends on the data used for the estimation (i.e., a state of the country). Chen et al. (2015) also analyzed the water footprint of the machine tools, identifying that the use stage dominates the water footprint.

Though other workpiece materials could be used in machining, metals such as aluminum, cast iron, steel and titanium are commonly used. Machining these materials is always demanding in terms of energy due to the associated heat and mechanical power requirements. Thus, the effects of workpiece materials should be evaluated. In this sense, Bonilla Hernández (2019) studied the influence of two materials on both energy consumption and CO_2 footprint. These two materials were: Ti-6Al-4V, a titanium alpha–beta-alloy in a solution-treated and aged condition, and MP159, a cobalt-base-super alloy, multiphase, in a solution-treated, cold-drawn and aged condition. The authors analyzed the material extraction, manufacturing, transport, use and end-of-life potential. The extraction of Ti-6Al-4V requires more energy and has a higher CO_2 footprint, while the contrary occurs for manufacture, transport and use. Moreover, the end-of-life potential (recycling) of Ti-6Al-4V is much higher than that of the MP159. Moreover, the machining requirements depend on the machinability of the material itself. For instance, the power required for machining depends on the material, as shown in Carou et al. (2015).

Cutting tools are made of a wide range of materials, such as high-speed steel, tungsten carbide, alumina, cubic boron nitride and polycrystalline diamond. In addition, a wide range of solutions are available for coating the substrate materials, for instance, titanium nitride, titanium carbo nitride and titanium aluminum nitride. Cutting tools and coatings requires large amounts of raw materials and energy. Thus, a conventional evaluation based on productivity must be accompanied by an ecological evaluation (Klocke et al., 2013). For instance, Li et al. (2017) studied the carbon emissions of coated inserts throughout their life cycle, identifying that 70–80% of these emissions were related to the usage phase.

Efforts are also being made in non-traditional machining processes to improve their sustainability by eliminating or reducing unsustainable raw materials. For instance, Dong et al. (2019) proposed an alternative material for removing kerosene from the electrical discharge machining (EDM) process by using a novel water in oil (W/O) nanoemulsion dielectric.

2.2 Energy

Machining involves a wide range of parameters that could affect a process's results in terms of the quality of the machined surfaces (Rubio et al., 2012), cutting tool wear and environmental impact. Moreover, different machining strategies may be employed to machine a specific part, affecting outcomes, such as power consumption. In this sense, Vila et al. (2015) studied various strategies in the milling of AISI D3 hardened steel by using a face mill with a 52 mm diameter and five carbide inserts featuring PVD AlCrN coatings. Mainly, the contour, one-way (X-axis), one-way (Y-axis), zigzag (X-axis) and zigzag (Y-axis) strategies were used. The authors related the power consumption to the CO_2 emissions, and the results showed how the milling strategy played an essential role in the amount of CO_2 emissions. Specifically, the results for the X-axis resulted in a more sustainable solution. In contrast, the zigzag strategies were more demanding regarding power consumption, placing the contour strategy in the middle. The material removal rate was also found to be critical for CO_2 emissions, which in connection to the strategy may increase them close to 50% from the optimum solution. Aramcharoen and Mativenga (2014) also studied the influence of the toolpath on energy consumption in the milling of T316L stainless steel. Similarly, the strategy taken to mill a part was studied by Campatelli et al. (2014) by changing the orientation of the workpiece and evaluating the energy consumption.

Energy consumption in machining is mainly due to the cutting forces required to cut the workpiece material. Thus, it depends on the type of material to be cut (i.e., its machinability). Anyway, the cutting power can be diminished using the selection of an optimized cutting speed. Although energy is not precisely linked to atmospheric emissions due to its dependency on the geography/energy mix (Linke et al., 2012), it is a good indicator of a machining process's environmental impact. Many studies on energy in machining have been presented over the past several years. Some of them are conveniently reviewed by researchers such as Peng and Xu (2014) and Yingjie (2014).

A study by Cica et al. (2020) provides a good example of examining energy (power) usage during the machining of AISI 1045 steel. The authors employed three regression-based machine learning techniques: polynomial regression, support vector regression and Gaussian process regression. These techniques allowed for predicting machining force, cutting power and cutting pressure. They involved selecting as machining parameters the cutting speed, the depth of cut and the feed rate. Wang et al. (2019) evaluated a machining process for prismatic geometries using the STEP-NC standards. Yip and To (2020) presented a model to assess energy consumption, in which both the material removal and the material recovery were included. The model was assessed through an experimental investigation using diamond tools to machine Ti-6Al-4V. Bi and Wang (2012) presented a study on energy consumption with a modeling method based on the kinematic and dynamic behaviors of chosen machinetools. Models were also developed for analyzing non-conventional processes, such as electro-discharge machining (Li & Kara, 2015).

Jia et al. (2018) evaluated the energy consumption of the machine-operator system using a model that includes the energy consumption of the operator, which is not usually done in energy studies in machining. After presenting the model, the authors showed an example of the CK6153i CNC machine-operator system identifying potential energy savings of 15.85%.

As discussed above, carbon emissions are related to energy consumption. In this sense, Jeswiet and Kara (2008) proposed a model for calculating CO_2 emissions based on the electrical energy consumed to produce a component or manufactured product by using the Carbon Emission Signature (CES™) as calculated for the energy mix. The authors used the method for analyzing the turning of a titanium bar and an aluminum bar. They used the compressing of an aluminum billet for the electrical grids of Ontario (Canada) and New South Wales (Australia). Mulyadi et al. (2015) employed the CES™ method to assess the milling of H13 tool steel. Global warming potential calculated from the cooling, tool change, cutting, ready, and setup energies clearly showed the influence of the used cooling environment. Mainly, dry and minimum quantity lubrication (MQL) conditions produced almost half of the emissions compared with the flood environment. Similar results were obtained when analyzing the acidification and human toxicity levels.

Machinetools, particularly old ones, can represent a source of higher energy consumption, as highlighted by Kianinejad et al. (2015). The authors identified that the specific energy consumption of the outdated milling machine was, on average, 40% higher than the newer one. Moreover, the configuration of the machinetool may affect energy consumption. In this sense, Harris et al. (2015) evaluated the influence of electric and pneumatic ultra-high-speed machines on energy consumption, highlighting that a turbine spindle consumes a considerably higher amount of power than an equivalently rated electric spindle tool does.

3 Life Cycle Assessment

The first initiatives to analyze the life cycle of materials and products can be traced back to the late 1960s and early 1970s (European Environment Agency, 1997). Notably, the Coca-Cola company conducted an LCA in 1969 (Hunt et al., 1996). LCA is a methodology or a "way of thinking" (Clark & de Leeuw, 1999). It aims at evaluating, in the most objective way possible, "the environmental loads associated with a product, process, or activity, identifying and quantifying the use of mass and energy as well as the emissions to the environment" to identify the environmental impact (Carvalho et al., 2011). The methodology uses several impact categories, such as climate change, resource depletion, ecotoxicity, etc. (European Comission, 2016). Mainly, a critical activity for developing LCA is accurately identifying and quantifying all input and output flows from the system (Ciroth el al., 2020; Ferrari et al., 2021).

Some authors identified LCA as a decision-support tool (Hertwich & Hammitt, 2001; Pryshlakivsky & Searcy, 2021). It is increasingly used as a management and product design tool (Malmqvist et al., 2011). This identification is essential when considering its main limitations. Companies can conduct LCAs to identify potential improvements in their manufacturing processes. LCA also can provide environmental data to the public or the government, identify best environmental practices and waste reduction options, and compare processes or products at multiple points during manufacture and use. Perhaps the most critical time for making decisions is during the design stages of new products. According to Rebitzer (2002), the generation of environmental impacts mainly occurs in the latter phases of the product's life cycle (i.e., end of life). Still, it must be considered that the environmental impacts are primarily determined during the design/development phase.

3.1 Methodology

LCA collects all inputs and outputs during the material flow process at every production step. The methodology is aimed at calculating the environmental impacts following four main steps, namely (International Organization for Standardization, 2006a, 2006b):

(i) Goal and scope definition, where the aim is described and the boundaries are fixed.
(ii) Life Cycle Inventory (LCI), where all the data related to the raw materials and energy corresponding to the studied system are collected. The inputs and outputs are assembled during the analysis at each manufacturing process step. LCI is the phase in which each environmental aspect of a system is compiled and quantified. Ferrari et al. (2021) stated that "the LCI is the most delicate and challenging phase."
(iii) Life cycle impact evaluation, where output emissions and input resources are clustered into impact groups and transformed into the same units for comparative assessment.
(iv) The interpretation of the LCI and effect evaluation.

Since the concept of Life Cycle Analysis appeared, numerous tools have been developed to facilitate the computation. Most available programs include databases, while others allow importing free and commercial databases to work with. The European Commission, Methodology Study Eco-Design of Energy-Using Products (MEEUP) classifies LCA studies according to computer tools, methodologies and databases.

Commercial software is available for properly conducting LCA. It should be noted that LCA software is generic and can be used for any industrial area. The tool's power and reliability rely on the database. Specific databases exist for chemical products, eco-design, industrial products and packaging. Some even allow users to associate costs and perform economic analysis. Tools exist for conducting LCA studies for virtually all specific products and sectors. Thus, they must be selected depending on the objective and scope established. Therefore, databases exist for different industries (plastics, food, construction, clothing, chemicals, etc.). Kalverkamp et al. (2020) identified some of the most used databases, for instance, ecoinvent, GaBi professional, Probas, the U.S. Life Cycle Inventory (USLCI) Database, the International reference Life Cycle Database (ILCD) and the Global LCA Data Access network (GLAD).

LCA must be considered a decision support tool. However, it should reflect on the tool's limitations. For instance, when attempting to conduct LCA, it should be considered that the type of information is merely an indicator. LCA should not be misunderstood as a complete assessment; it extensively uses subjective judgment, and the lack of scientific or technical data is sometimes apparent (European Environment Agency, 1997). For instance, De Rosa et al. (2018) indicated that methodological choices might have a significant effect on the LCA outcomes. Other researchers, such as Hélias and Servien (2021), claimed that the need still exists to advance in using the same data sources and normalization references.

3.2 LCA of MachineTools

Machinetools are complex systems composed of mechanical, electrical and fluid-powered devices (Zendoia et al., 2014). The objective of a machine tool is to allow for the manufacturing of parts according to the dimensional and geometrical requirements (Duflou et al., 2012). Machine tools should have high stiffness and damping capacity, which is generally guaranteed by heavy structures (i.e., mainly cast iron; Marichelvam et al., 2021), to meet the requirements.

In general, the life cycle stages of machine tools used to calculate their environmental impacts are as follows (Cao et al., 2012; Hu et al., 2012):

- *Material production*: material extraction, processing, heat treatment, etc.
- *Use*: it is an energy-intensive stage due to the power needs for operating the machines (e.g., axis movements, tool changes, etc.) and the high cutting power consumed during operation. The environmental impact in this phase is the highest.
- *Transport*: it works as a bridge among the other life cycle stages.

By note of caution, it is essential to indicate that generally, the manufacturers of the machine tools, cutting tools, jigs, fixtures, etc. are not willing to release specific details. For instance, they consider that the types of materials, their weights, and their processing details are crucial and "proprietary" information. This lack of knowledge is one of the main inconveniences in developing completely reliable LCAs.

4 Life Cycle Assessment in Machining

4.1 Studies in Machining Processes

In Sect. 2, several strategies oriented toward sustainability in machining were identified. LCA is a suitable tool for machining processes because it considers the whole process, including all inputs/outputs. However, it could also be used to analyze a specific part of the process—for example, to evaluate the utilization phase of the machine tool (González, 2007). In the last years, researchers have paid increased attention to the application of LCA in machining as can be seen in Fig. 2. The graph shows an increasing number of results for "life cycle assessment" AND "machining" in the Scopus database using the "all fields" option.

The assessment presented in this chapter offers a big picture of the use of a machining methodology that allows actions to suppress or at least diminish the environmental impacts. Next, some experimental studies that employ the LCA approach in machining are reviewed and summarized in Table 1.

Gupta et al. (2020) analyzed the use of different turning conditions in the machining of pure titanium. The results were analyzed using SimaPro 8.3 using two databases: EPS 2000 and ReCiPe Endpoint v1.12. Both methods offer similar

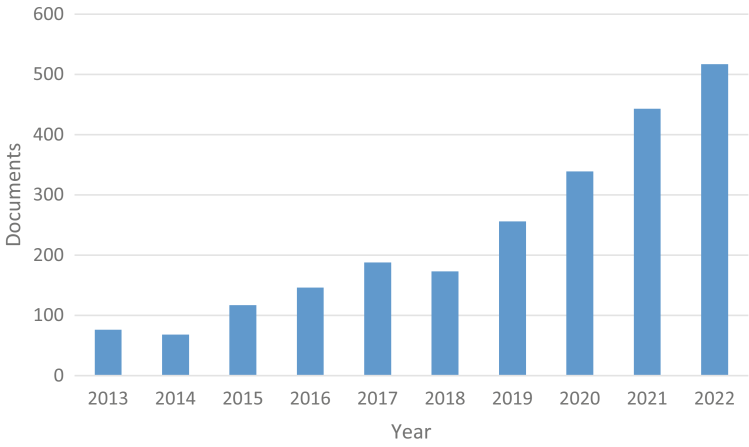

Fig. 2 Documents in Scopus database for "life cycle assessment" and machining between 2013 and 2022 according to Scopus on February 13, 2023

results. Based on their study, the authors stated that the most significant impacts depend on energy consumption.

Mia et al. (2019) conducted an experimental study on the turning of the Ti-6Al-4V alloy. The experimental tests included dry machining and cryogenic machining (mono and dual jet) using liquid nitrogen tests. The LCA was carried out with SimaPro 8.3 using two databases: EPS 2000 and ReCiPe Endpoint v1.12. The results showed that dry machining requires higher cutting forces than the cryogenic alternative. Thus, the experimental tests with the higher environmental impact are those in which dry machining conditions were used.

Campitelli et al. (2019) studied the drilling and milling of aluminum alloy, cast iron and steel. The software used for carrying out the LCA was the LCA 1.4.2. The database was the ecoinvent 3.1. The CML 2001 method was used, and one of the main results included the recognition of flood cooling as the most important reason for increasing the environmental impact. The higher effect was due to an increase in energy consumption due to pumping and fluid consumption against the minimum quantity lubrication system. Furthermore, flood cooling generates hazardous waste. The major impacts of cutting fluids are associated with land use and terrestrial ecotoxicity. The researchers highlighted electricity, compressed air and flood lubrication oil as key factors for improving the process's environmental efficiency.

Filleti et al. (2017) evaluated using CBN and Al_2O_3 grinding wheels on the machining of Inconel 751. The study was performed using GABI software, and the UPLCI methodology allowed for identifying energy as the main contributor to the impact categories studied. Besides, it was possible to find that the material removal rate greatly influenced the results. Moreover, some subunits (e.g., hydraulic, cooling,

Table 1 Summary of experimental studies in machining using LCA

Author	Software/methodology	Methods	Machining process/workpiece material/tool material/cutting environment	Environmental impact
Gupta et al. (2020)	Simapro 8.3	EPS 2000 ReCiPe Endpoint v1.12	Turning Pure titanium Uncoated carbide MQL and Ranque-Hilsch Vortex Tube assisted Minimum Quantity Cutting Fluids	Human health, ecosystem production capacity, abiotic stock resource, biodiversity Human health, ecosystems, resources
Mia et al. (2019)	Simapro 8.3	EPS 2000 ReCiPe Endpoint v1.12	Turning Ti-6Al-4V Multi-layered TiCN/Al_2O_3/TiN coatedWC Dry, and mono and dual-jet cryogenic cooling	Human health, ecosystem production capacity, abiotic stock resource, biodiversity Human health, ecosystems, resources
Campitelli et al. (2019)	Open LCA 1.4.2	Ecoinvent v3.1	Drilling and milling Aluminum, cast iron and steel Solid-carbide and hard metal MQL and flood	Fourteen impact categories from CML 2001
Filleti et al. (2017)	GaBi 6—UPLCI	GaBi	Grinding Inconel 751 alloy Al_2O_3 (JB126 K150 VSS) and CBN (8B126 K150 VT2) Flood	Global warming potential, Ozone layer depletion potential, Acidification potential, Photochemical oxidation potential, Nutrient enrichment potential, Chronic water ecotoxicity potential, Acute water ecotoxicity potential, Chronic soil ecotoxicity potential, human toxicity potential via soil, human toxicity potential via water, human toxicity potential via air

(continued)

Table 1 (continued)

Author	Software/methodology	Methods	Machining process/workpiece material/tool material/cutting environment	Environmental impact
Damir et al. (2018)	Not available	Eco-indicator 99	Turning Ti-6Al-4V CNGP 120408 Sandvik, CVD coating Cryogenic and flood	Single score indicator
Gamage et al. (2016)	SimaPro 8	Ecoinvent v3.0 ReCiPe Endpoint (H) V1.11/Europe ReCiPe H/A Single score method	Electrical discharge machining: die sinking and wire Aluminum (3003) Copper and Brass Water	Machining wastes in solid, liquid, gas and aerosol
Liu et al. (2018b)	Not available	Eco-indicator 99	Milling Inconel 718 Tungsten carbide, (Ti,Al)N/TiN coating SECO XOEX 120408R-M07 F40M Dry and flood	Impact measured in milli-point (mPt)
Zanuto et al. (2019)	GaBi 6	Ecoinvent	Milling AISI P20 steel TiN-coated carbide and uncoated high-speed steel Lubricating oil (organic)	Abiotic depletion potential, Abiotic depletion potential, Acidification potential, Eutrophication potential, Freshwater aquatic ecotoxicity potential, Global warming potential, human toxicity potential, Marine aquatic ecotoxicity potential, Ozone layer depletion potential, Photochemical ozone creation potential, Terrestrial ecotoxicity potential

(continued)

Table 1 (continued)

Author	Software/methodology	Methods	Machining process/workpiece material/tool material/cutting environment	Environmental impact
Shi et al. (2021)	Not available	CLCD database	Turning Low-carbon alloy steel Steel Flood (water–oil)	Massive consumption of primary resources and generation of massive amounts of greenhouse gases
Shah et al. (2021)	Ecochain Mobius	ReCiPe 2016 midpoint (H)	Drilling Inconel 718 Coated solid carbide Liquid carbon dioxide and liquid nitrogen	Impacts on the environment, human health, and depletion of natural resources

cutting fluid pumping and exhaustion) may be optimized to notably reduce the environmental impacts, considering that they explain 45 to 70% of the electric energy consumption.

Damir et al. (2018) evaluated the influence of cryogenic and flood cooling in the turning of Ti-6Al-4V. LCA was carried out based on the Eco Indicator 99 method. As process inputs for flood cooling, it was considered to involve flood oil production, transport, machining and pumping. Meanwhile, as inputs for the cryogenic method, it was supposed to involve LiN production and transport, as well as Ni liquefaction and machining. The single indicator used as the output showed how the cryogenic method has a lower score than the flood method. The only positive activity of flood cooling is the recycled lubricant. Thus, the possibility of recycling the lubricant improves the total single score indicator. Sill, in any case, the total value is higher than that of cryogenic cooling, mainly due to lubricant production.

Gamage et al. (2016) evaluated electrical discharge machining with SimaPro software to evaluate energy consumption, tooling, cutting fluid and compressed air. The authors found that electricity was the major contributor to the environmental impact, representing 57 and 60% for die sinking and wire EDM, respectively. After that, in die sinking, dielectric oil accounted for 27% of the environmental impact, whereas 38% was due to the tooling (brass) in the wire EDM.

Liu et al. (2018b) used the Eco-Indicator 99 to assess the environmental impact of the milling of Inconel 718. Two cooling conditions were used: dry and flood. The authors discovered that the contribution of the workpiece material was high, from 30 to 50%, and that as the milling conditions increased, the contribution of the cutting tool consumption notably increased while diminishing the impact associated with energy consumption.

Zanuto et al. (2019) studied various strategies in the milling of AISI P20 steel. Gabi software was used to carry out the analysis. When referring to the inputs, the authors identified high deviations in the data provided through the software, leading to a high uncertainty level. Specifically, according to the software inventory, the amounts of the analyzed resources for milling 1.0 kg of low-alloy steel were given with a standard deviation from 105 to 332%. Some findings included the identification of slow speeds as a cause of more considerable environmental impacts. Thus, high-speed steels lead to more significant impacts than carbide tools do due to their slower speed requirements.

Shi et al. (2021) conducted a case study on the turning of low-carbon alloy steel parts. Using the LCA methodology, and per ISO 14955-1 (International Organization for Standardization, 2017), the authors analyzed the inventory data for energy and material consumption, as well as waste emissions, evaluating them for five categories of environmental impact. Their results showed that PED (primary energy demand), which includes three non-renewable sources of energy, and GWP (global warming potential) are the categories that offer the most significant environmental impact in this type of process. They further suggest that its environmental performance could be improved by increasing the cutting efficiency and using low-environmental load materials for the turning unit.

Shah et al. (2021) analyzed the drilling of an IN718 plate with solid carbide drills by using two cryogenic environments: liquid carbon dioxide (LCO2) and liquid nitrogen (LN2). They used tool wear, energy consumption and surface roughness as parameters. The study considered three cutting speeds, and the authors found that LCO2 increased drilling efficiency (between 25 and 300%). In addition, LCO2 reduced the pushing force by 14%, energy consumption by 19% and surface roughness by 11%. However, the LCA analysis showed that LN2 had a lower ecological impact in 17 of the 18 categories analyzed.

4.2 *Studies on Machining and Alternative Processes*

LCA can also be used as a comparative tool for assessing the suitability of a specific manufacturing process against others depending on the environmental impact. However, in this case, the complexity increases as more data are required to adequately model the processes, using very different machines based on other operating principles. Thus, the materials used and the energy needed to operate can vastly vary. Moreover, in most cases, data are unavailable and should be estimated. Some of the major scientific studies are briefly reviewed and summarized in Table 2.

Ingarao et al. (2018) compared additive manufacturing (selective laser melting), forming and machining (turning) using LCA. Parts were made of high-strength AA-7075 T6 aluminum alloy. The Ecopoint was the selected impact metric by the authors. The impact categories were calculated by applying the ReCiPe method H/A, an update of the Eco-Indicator 99 and CML 2002 methods. Different geometries were evaluated, and even for the most suitable geometry for additive manufacturing, it was found that the environmental impact of additive manufacturing was higher than that of conventional machining due to the high-energy intensity of processing for additive manufacturing. The weight reduction provided through additive manufacturing helps

Table 2 Summary of the main processes versus machining using LCA

Author	Machining process	Alternative process
Ingarao et al. (2018)	Turning	Additive manufacturing (selective laser melting) and forming
Serres et al. (2011)	Conventional machining	*Construction Laser Additive Directe*, in French (CLAD)
Deboer et al. (2021)	Machining	Casting (forming), and three additive manufacturing methods (binder jetting, powder bed fusion and bound powder extrusion)
Bekker and Verlinden (2018)	CNC milling	Wire arc additive manufacturing, green sand casting
Zendoia et al. (2014)	Milling, drilling and boring	Abrasive water jet machining
Jiang et al. (2019)	Grinding and milling	Laser engineered net shaping

to reduce transport impacts but still does not compensate for energy requirements for manufacturing.

Serres et al. (2011) compared the direct additive laser manufacturing (CLAD) approach with the conventional machining of Ti-6Al-4V. Additive manufacturing proved to be a more sustainable solution using LCA (Ecoscore from Eco-Indicator 99 methodology) mainly due to the high mass of chips in machining, which could reach up to 80% of the total consumption.

Deboer et al. (2021) carried out a comparative study through the LCA of various categories of manufacturing processes: casting (forming), machining (subtractive) and three additive manufacturing methods (binder jetting, powder bed fusion and bound powder extrusion). Using three environmental metrics (water consumption, energy requirements and CO_2 emissions), the authors evaluated the life cycle of a double cardan H-yoke. Their findings showed that forming is the most environmentally friendly process for large-scale production. Among additive manufacturing technologies, powder bed fusion combined with renewable energy was the most environmentally friendly option, reducing CO_2 emissions by 9.2% compared to casting. Finally, they found that machining has the worst performance from an environmental perspective due to the amount of waste material.

Bekker and Verlinden (2018) compared the environmental impacts of wire arc additive manufacturing, green sand casting and CNC milling of 308L stainless steel based on data taken from ecoinvent 3. ReCiPe endpoint totals showed that the material contribution was dominant. Therefore, additive manufacturing outperforms CNC milling when the material use increases because of the ability of additive manufacturing to decrease the weight of the part due to topology optimization.

Zendoia et al. (2014) presented a comparative study of abrasive water jet machining versus a set of conventional operations (milling, drilling and boring) for one aeronautical part, using SimaPro7 Analyst based on the ecoinvent database. The authors stated that further work is still required to evaluate the alternative route to justify the substitution when dealing with larger batch sizes.

Jiang et al. (2019) compared CNC machining (grinding and milling) and the laser engineered net shaping (LENS) process to manufacture gears of AISI 4140 steel. The authors used the GABI software, identifying that the LENS process is more sustainable than the CNC machining.

5 Implications and Insights

5.1 The Importance of Machinability

In Sect. 4.1, a review of recent studies on using LCA in machining was presented. No comparisons were made between these studies. One reason for this is that different processes were included (turning, milling, grinding, etc.) that have essential differences in terms of issues, such as the material removal rate. Moreover, the nature and elements of traditional mechanical machining processes are different from those of non-traditional processes, such as the electrical discharge machining process, a thermal-based method.

A key issue to consider is the machinability of the materials. It is well known that the different machinability of the materials demands other machining conditions. In this sense, materials such as aluminum, nickel-based and titanium alloys, and steels require different amounts of cutting power to be machined (Polmear, 2005; Carou et al., 2015). Conventionally, cutting power is approximated using Eq. 1, thus depending on the cutting force (F_c) and the cutting speed (v) (Khan et al., 2020).

$$P_c = F_c \times v \tag{1}$$

By way of example, research on the conventional turning of Ti-6Al-4V alloy in semi-finishing conditions requires cutting speeds from 40 to 100 m/min (Lindvall et al., 2021). Difficult-to-cut materials are "easier" to cut by using low cutting speeds. In this sense, the cutting speed ranges for materials such as nickel superalloys are like those of titanium alloys. For instance, Thrinadh et al. (2020) turned Inconel 718 using cutting speeds from 65 to 85 m/min. However, when it comes to materials with better machinability, the cutting speed can be immensely increased. For instance, Abas et al. (2020) used cutting speeds from 400 to 700 m/min to turn the 6026-T9 aluminum alloy.

The machinability of various materials drives researchers and practitioners to select different cutting tool materials among those available. They may also have to use cutting fluids or suitable alternatives. Uncoated cemented carbides are conventionally used for titanium alloys (Lindvall et al., 2021), while coatings such as TiB_2, TiC, TiN, and Al_2O_3 are improving the machining of aluminum alloys (Rao & Gopal, 2021). The influence of the processing of the cutting tool material on the environmental impact is critical. Moreover, tool wear plays a crucial role in the process due to its effect on productivity (i.e., number of inserts, tool changes, etc.). Most of the LCA research does not include a detailed evaluation of the impact of tool wear. In this regard, the study by Kim et al. (2021) is worth noting. The authors presented a detailed study on tool wear for both ceramic and CBN inserts using cryogenic, dry and wet machining, relating CO_2 emissions to the tool life under the analyzed machining conditions.

5.2 *Energy Evaluation*

Energy consumption is a critical input for LCA. Commercial software can be used to estimate energy consumption in machining, but it may be underestimated, as He et al. (2022) pointed out. In machining, cutting and non-cutting times coexist. Thus, Eq. 1 allows for the accounting of only a part of the total energy consumption. In this sense, it should be considered the demands for the spindle, axes motion, cutting resistance (workpiece materials, cutting tool and cutting conditions) and others (cutting fluid pump, cooling device, computer controller) (Aramcharoen & Mativenga, 2014). The number and complexity of the tasks involved in machining make it challenging to estimate energy consumption with accuracy.

To understand and estimate energy consumption, researchers have developed energy consumption models. Aramcharoen and Mativenga (2014) critically reviewed eight models developed from 2006 to 2013. According to the authors, one of the major drawbacks of the existing models is that they do not fully capture the complexity of the machining process, and some tasks that consume energy are not included. The development of fully comprehensive models for energy consumption is a requirement for the LCA because omissions may compromise the results.

When energy consumption is divided into several tasks, the results of the LCA can be more helpful, as they can help to identify the contribution of different sources of environmental impacts. For instance, this is clear when attending to the cutting environment. The type of raw material used as environment influences the impacts and the energy required for the cooling/refrigeration system. Some models do not include the proper assessment of the energy that the cutting fluid system or alternatives consume (Mulyadi et al., 2015).

In addition, the same machining operation can be performed using different strategies. It should be noted that a large amount of energy, up to 30%, is consumed in non-cutting operations (e.g., tool path, tool change and change of spindle rotation speed; Hu et al., 2017). Because of this, LCA must be carried out by approaching the analysis of energy consumption "line by line" through the CNC code, as using only cutting operations or uncomprehensive analysis results in improper assessments.

5.3 Applicability

Comparisons among different experimental studies are difficult to make when the workpiece material, cutting parameters, tools and machine tool are different (Zanuto et al., 2019). Specifically, these studies are not standardized, and the analysis largely depends on the authors' knowledge and juice.

In recent years, the number of experimental studies on LCA in machining has increased. However, the software/methodologies and methods, the processes analyzed, the tool and workpiece materials, and the cutting environments are not uniform, as shown in Table 1. The same applies to comparative studies among the manufacturing processes listed in Table 2. However, some insights can be obtained from the previous examples:

- First, the LCA methodology allows researchers and practitioners to evaluate the influence of their machining strategies on the environment. In this sense, evaluating the impact, by comparison, is reasonably straightforward when they have a suitable LCA methodology. It is true that, in some cases, it requires effort to create accurate inventories. For instance, it may require performing experiments to quantify inputs, such as energy consumption accurately, or to develop detailed models for this. However, in the end, LCA may help determine the influence of alternative cutting environments, cutting tools or cutting parameters.

- Second, the influence of the factors is complex. No single factor always causes a major increase in the environmental impact of machining. In this regard, the studies allowed readers to identify how critical the cooling/refrigeration system is in some instances, whereas electricity is essential to others. By way of caution, it is important to note that the baseline for comparison in all cases is not the same. In other words, no "worst case" scenario exists for comparisons. This issue is evident when one is attending to the cooling/system. Thus, some use conventional/flood cooling, which can be deemed the "worst case" scenario, but others use more sustainable alternatives, such as MQL or cryogenic machining. In this sense, the importance of the cooling/lubricating system in terms of sustainability may be blurred. However, it needs to detail all the inputs related to the cutting environment, particularly those related to energy consumption.
- Third, the comparison increases its difficulty when it is made between two or more processes. Thus, researchers need to generate an inventory for each of the processes. The power of these studies relies on the fact that the variations in the effects may be more significant. In any case, process substitution can hardly be decided solely based on the environmental impact. The evaluations must consider aspects such as the productivity of the process, the quality of the resulting parts and the investment.

6 Conclusions and Future Work

Sustainability has gained relevance in the last decades. Manufacturing is one of the main contributors to environmental issues, such as energy consumption, environmentally damaging cooling/refrigeration strategies or the intensive use of raw materials. Thus, manufacturing is one of the targets for implementing sustainable practices. Life Cycle Assessment has been identified as one of the most promising initiatives.

Nowadays, machining is still one of the most important manufacturing processes for industry. Machining is a process in which raw materials and energy consumption is critical. Its widespread adoption has encouraged companies to adopt "green" practices. As a result, this chapter presents an introduction to the use of LCA in machining. In the review, it is possible to identify several studies using different software and methodologies to evaluate machining's impact on the environment. Moreover, it is possible to highlight studies in which machining is compared with other manufacturing processes.

These LCA studies can be considered the first stones that may lead to a more profound knowledge about the industrial operations' impacts on the environment. LCA has already proved to be a suitable methodology for comparisons, mainly varying operating conditions among several. For instance, this can be helpful when fixing critical factors such as the workpiece material because of the influence of machinability on the settings, as discussed.

Detailed, complete and reliable LCAs in machining are still far from being obtained, mainly due to the complexity of the machining process. Particularly, this is due to the absence of data regarding the materials used to produce machine tools and cutting tools (i.e., materials and weights), and the details of the processing of these materials. Thus, knowing the exact amount of materials, energy, and water required to produce a machine tool remains an "educated guess". In this sense, LCAs are simplified when focusing on operating conditions. Issues such as energy consumption are also complex to address and demand great effort from researchers. In the years to come, machine tool manufacturers will likely produce machines with advanced capabilities in terms of the electrical consumption analysis linked to the sensorization wave drive by Industry 4.0, which could help in accurately evaluating environmental impacts.

In the future, it would be helpful that all commercial materials, tools and machine tools would be accompanied by full certificates in which complete details regarding inputs would be indicated. In this sense, full traceability may be possible, representing a massive driver for the LCA methodology, not only for machining but also for a wide range of activities. Thus, voluntary initiatives, such as the European Ecolabel,[1] may serve as a base for providing LCA practitioners with improved data for conducting their analyses.

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[1] European Ecolabel: https://ec.europa.eu/environment/ecolabel/index_en.htm.

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