Abstract The interest in pollution prevention is continuously growing. This determines several industries, including manufacturing, to develop and implement various environmentally-friendly strategies. Product design, selection of raw materials, manufacturing process, product delivery and reuse or recycling options for products’ end of life have influences for the of environmental degradation level. There is an ongoing search for new and innovative ways by which industry can lessen its impact on the environment. Efforts are currently focused to: efficient consumption of resources and conserve energy, minimize the environmental effects of energy production, improve waste management system. This chapter presents several aspects regarding the environmental impact of manufacturing process and the necessity of changed process for increasing their sustainability and thus, preventing polluting generation. It is mainly focused on investigating various aspects of machining process from an environmental perspective.

1 Introduction

The society has generally two kinds of interactions the environment: as a source for natural resources, and as a landfill for solid, gaseous and liquid wastes. The damages act as depletion and the reduced quantity and quality of resources and as unbalancing the conditions of previously natural processes. The change in balance takes usually years to detect and can be influenced by a variety of factors. This issue makes identification and isolation of the problems difficult and sometimes controversial.
The studies done in this direction leads to identification of several aspects concerning the environment depreciation: ozone depletion, global warming, acidification, and eutrophication. Corrective actions involve changes in the types and ways it uses materials and energy for the production, use, and disposal of products.

A life cycle assessment scheme can properly link each product or process with its environmental load. Although this task is conceptually simple, it is quite complex in fact. The major complexities originate in difficulties to: establish the system boundaries, obtain accurate data, represent the data with concise descriptors that appropriately assign responsibility, and to evaluate properly the results.

The idea of a product life cycle is generally regarded as a materials flow process that starts with extraction of raw materials and ends with the disposal of the waste products. The general stages of this linear cycle are: material extraction, primary processing and refining (premanufacture), product manufacture, product distribution, use, and final disposition. This sequence follows the principal product material flow, but of course there are multiple cross flows (secondary flows) as well as backflows (part remanufacturing, product reuse, or material recycling). For each of these stages the environmental stressors are: materials choice, energy use, solid waste, liquid residues, and gaseous residues [1].

The manufacturing processes seem to be quite benign compared to materials extraction and primary processing, but manufacturing processes set many of the requirements for primary processing outputs. Normally, the processes with higher scrap rates require more energy in primary processing, while processes which use large quantities of recycled materials will have reduced primary energy needs.

Concluding the manufacturing uses materials and energy (not directly incorporated into the product) and then eliminates them as wastes or emissions to the environment. In addition to work pieces, tools and energy, a second environmentally important category of auxiliary materials used in manufacturing processes is metalworking fluids, cleaning fluids and coatings. Lubricants and solvents are of particular concern, being used to remove the coolant or lubricants from the surface of the parts [1].

2 Sustainable Manufacturing Technologies

Sustainable manufacturing is a relatively less-known and significantly element of sustainable development, including three functional elements: sustainable products, processes, and systems. It is important to develop quantitative predictive models for sustainable product design and manufacture in order to understand the integral role of these elements of sustainability in product manufacture.

One of major challenges to the industry is to design and manufacture sustainable and environment-friendly products. Such process involves complex, interdisciplinary approaches and solutions. According to definition of sustainability, the sustainable products are fully compatible with environment throughout their life cycle. The manufacturing processes must exceed beyond their traditional
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requirements of functionality, cost, performance, and time-to-market, by considering also sustainability. This would be possible by thinking in terms of reduced material utilization, minimizing energy consumption, waste-free manufacturing processes, and resource recovery following the appropriate end of product scenario [2].

In recent times the goal of reuse, recycling, and remanufacturing emerged with innovative engineered materials, manufacturing processes, and systems aiming to provide multiple life-cycle products. The need for ecological efficiency and the environmental concerns are often associated with production of minimum waste amounts, minimum toxic emissions into the air, soil, and water, and minimum energy consumption at all life cycle stages (Fig. 1).

The companies have the potential to save costs and to improve their environmental performance even the production stays on the same size or it is decreased. This is possible with the implementation of the sustainability principles in the manufacturing processes [3–6].

Fig. 1 Typical life cycle stages
As already known, machining is a material removal process that typically involves the cutting of metals using various cutting tools. A process that removes material, machining can be inherently wasteful due its use of raw materials (workpieces) and energy. Machining processes are particularly useful due to their high dimensional accuracy, process flexibility, and cost-effectiveness in parts’ producing. Machining is unique, among manufacturing processes, in that it can be used both to fabricate products and to finish products [7].

Overall production process of a component consists of several elements and steps: process inputs (material, energy, data), machining, cooling/lubrication, part cleaning, preparation of chips to be disposed and their interactions [8–10] as shown in the Fig. 2.

Major environmental hazards in machining operations are due to the use of cutting fluids [11]. Direct exposure of the production worker to these fluids can lead to skin diseases and respiratory disorders and there is also an increased health risks [12]. The cause is attributable to both the original constituents in the fluid and impurities which are introduced or generated during operation. Losses of cutting fluid from the manufacturing process occur through vaporization, loss with chips and work pieces as they leave the machine, loss with machine components such as manipulation and transport devices, as well as losses through vacuum and air pressure systems and through droplet formation and ensuing leakage [13].

Fig. 2 Overall machining process of a part
Up to 30% of the annual cutting fluid consumption is lost through removal from the system by the above means. In addition, contamination of chips generated makes them difficult to recycle and work pieces must frequently be cleaned before proceeding to the next process step. Such cleaning operations are non-value adding and can also add to the overall environmental issues of the manufacturing system. In addition to environmental impact, it has been estimated that the use of cutting fluid can account for over 15% of machining costs [14].

There are several ways to reduce or avoid the usage of cooling lubricating fluids (CLF). The question that occurs is what kind of CLFs and how much of each have to be used to the manufacturing processes and their costs. In the case of conventional CLFs, their purchase costs have to be increased taking into account CLFs disposal costs, parts cleaning and drying, depreciation costs, maintenance costs and the costs connected with personnel and health issues. Dry cutting therefore results in both environmental and economic benefits.

## 2.1 Dry Machining and Near-Dry Machining

In normal machining operations, CLFs are used to flood the area of contact between the tool and the work piece. The most radical approach is to convert conventional flood cooling to dry cutting which eliminates all problems associated with cutting fluids. The process carried out in the absence of CLFs is called dry machining (DM), or near-dry machining (NDM) when the process runs in the presence of a very small quantity of lubricants, in the range of 10–150 ml/h, delivered in the cutting zone in a mist way. Dry cutting is made possible by recent developments in cutting tool materials, but presents new challenges in the areas of chip handling and machine tool design. Thus, the use of NDM [called also Minimal Quantity Lubrication (MQL)] is the way that can lead to a significant cost reduction of the process [15].

By simply avoiding CLF usage and applying DM alternative (using additionally new high performance coated cutting tools), there would be a huge progress for sustainable technologies [16, 17, 18, 19]. But, there are new work piece materials used especially in aerospace industry (such as nickel alloys, titanium alloys, Co-Cr alloys) which are extremely difficult to machine. In combination with high cutting speed, serious difficulties will be encountered, disabling the use of DM.

Tasks of coolants/lubricants, in the case of their absence have to be taken by other machining process components. In this respect, the latest technique concerns in demonstrating the application of modified tool for DM use [20]. A solid lubricant (molybdenum disulfide) was filled into the micro-holes on the rake or rake and flank face of the cemented carbide (WC/Co) tools in order to create self-lubricated tools. During dry-cutting of hardened steel, the cutting forces, the tool wear and the friction coefficient at the tool-chip interface using a such tool are significantly lower compared with the use of a conventional WC/Co tools. This effect is caused by the self-lubrication action of the modified tool.
For both technologically and economically optimal results, the NDM must be considered as a system having the following components: CLF feed technology, NDM media, parameter settings, tools and machine tools. The principle of this technique is schematically presented in Fig. 3.

In NDM the most commonly used media are synthetic esters and fatty alcohols, but some applications are still using emulsions or water (Table 1). Such high-performance oils have excellent lubricity and biodegradability properties and they are environmentally friendly [21, 22].

These fluid media are fed in very small quantity to machining area with or without the assistance of a transport medium. In the case of air-less systems a pump delivers CLF in the form of a rapid succession of precision-metered droplets. In the case of high pressure systems, the medium is atomized to form extremely fine droplets delivered to machining point in form of aerosol spray using compressed air at 4–6 bar pressure.

CLF delivery system can be an external supply with one or more nozzles fitted separately in the machine area or an internal supply of the media using the channels built into the tool body. Important roles in the quality of process results play the following elements: number, direction and emplacement of nozzles.

A distinction should be done between MQL and minimal quantity cooling (MQC) depending on the type and main functions of CLF. When good lubrication properties are needed than oils are used as cutting fluids, their function being to reduce friction and adhesion between work piece, chips and tool and thus the amount of friction heat generated. Much less frequently than oils, are used emulsions and water, when it is essential to cool more efficiently the tool or the part. These operations are regarded as MQC [22].
There are several application areas for DM and MQL. It involves a wide range of material—process combinations such as drilling, reaming, tapping, milling turning, gear milling, sawing, broaching, grinding, respectively aluminum, aluminum alloys, high alloyed bearing steel, tempered steel, cast irons.

CLFs avoidance requires alternative solutions that can be achieved through appropriate design of machine tools. The primary functions of the cooling lubricants from flood cooling process should be overtaken from other system components or solved by other technical solutions. In order to be suitable for DM, the design changes of existing equipment could require a lot of effort and high costs. Thus, if the machine tools rebuilding is not economically feasible, the application of MQL supply system and the housing of working area are usually a reasonable and necessary changes [22, 23].

For the new developed machine tools, the possibility to make substantial design modifications is easier, since requirements are known from the beginning. There is not only a single practical solution concerning the boundary conditions, since the manufacturing equipments are so different (individual machine tools, transfer lines, machining centers etc). In mass production and flexible manufacturing systems, the demands concerning the manufacturing structures changes can be divided in several classes: chip removal from the working area, temperature compensation, MQL system integration, and safety measures [22, 24].

With the increasing trends in the achieving sustainable machining, DM and NDM are emerging as viable and sustainable alternatives to the flood cooling (FC) in the machining processes. Even NDM is slowly being accepted as an alternative to FC and provides up to 80 % longer tool life, further studies are needed to find the best design of external nozzles and getting the right amount of fluid to the cutting point.

Use of these two machining methods could offer the possibility for efficiency increasing, due to the lubricants elimination in the form of conditioned waste, the process chain optimization, and the improvement of the work environment as well. The procedure is strongly dependent on the concrete process characteristics, the material properties of work piece and cutting tool.
2.2 Cryogenic Machining

Another innovative method of cooling the cutting area (cutting tool and/or work piece) during the cutting process is the cryogenic machining (CM). This is a very effective machining technique that utilizes a cryogenic CLF as coolant to bring down the temperature at the chip-tool interface, reducing the tool wear or to change the characteristics of material and, thus, improve machining performance and product quality [20, 25]. By researches four cryogenic approaches have been attempted: work-piece pre cooling, indirect cryogenic cooling, and cryogenic jet spraying and direct cryogenic treatment of cutting tools.

Usually the coolant used is a safe, noncombustible and non-corrosive gas (nitrogen), liquefied by cooling to $-196 \, ^\circ \text{C}$. It is not usual to employ the air as coolant since all gases have relatively poor cooling properties compared with liquids. Better cooling performances have been achieved by refrigerating the gases, high pressure of gases being also considered an additional help.

Basic principle of this process and the liquid nitrogen (LN) production process are schematically presented in Fig. 4. LN returns to the atmosphere by evaporating quickly in the cryogenic machining system, it leaves no residue to contaminate the parts, chips, machine tool and operator and the coolant disposal costs are eliminated.

CM can be successfully used in machining of difficult-to-machine materials, hard materials, high abrasive materials, or super alloys [26]. The method, introduced first in industry in 2003, was specially developed for turning and some

![Fig. 4 Schematic diagram of cryogenic cooling setup](image-url)
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milling applications. Nowadays it is implemented for high speed machining for hard and super alloys in aerospace and automobile industries. The tool manufacturers produce new machine tools that utilize cryogenic machining technology [27].

Other improvements consist of a faster machining process, a higher parts’ quality, a better machining performance, and an overall cost reduction. Summarizing, some of advantages of CM are: reduced chip-tool interface temperature, reduced tool wear, higher production rates, greater product quality, power saving, no mist collection, no filtration, no wet chips, no contaminated work piece or disposal costs. The main disadvantages of this technique are the additional equipment costs and the high price of LN, which is not reusable.

This technique can be considered a sustainable machining being a clean, safe and environmental-friendly method. It allows increasing the process productivity by a higher material removal rate without an increase of tool wear and with a reduced cutting tool changeover costs.

2.3 High Pressure Jet Assisted Machining

Even the trend in machining is the implementation on the large scale of DM and NDM (combined with the most advanced tool materials and coatings) in order to reduce the consumption of cutting fluids [22, 24], there are cases when the lubricants can not be completely avoided. One of the techniques developed to replace the conventional process, keeping or even increasing the machining performance, is high pressure jet-assisted machining (HPJAM).

HPJAM is another innovative method of lubricating/cooling the tool-chip interface during the cutting process, using the thermal and mechanical properties of a high-pressure jet of water or emulsion directed into the cutting zone. This technique is related to delivering the oil-based or water-based CLF under extremely high pressure in the range 80–360 MPa to the cutting tool tip through small diameter nozzles (0.15–0.25 mm) [3, 4, 24, 28]. The basic principle of HPJAM is shown in Fig. 5.

![Fig. 5 Schematic diagram of high pressure jet assisted machining](image)
Compared to conventional flood, the CLF flow rate is in this case relatively small. Due to their higher flexibility, external nozzles are widely utilized compared to internal channels. Having a high pressure, the CLF jet can penetrate closer to the share zone and cools it. The fluid jet is directed to the cutting edge at a low angle directly between the rake face and the chip.

Besides the cooling effect this method allows the control of the friction conditions between the tool rake face and the chip back side, leading to a machining performance improvement. The initial goal of HPJAM was an important increase of material removal rate and process productivity of advanced materials such as hardened steels used for moulds, Ni-based and Ti-based alloys used in gas turbines, Cr-Co alloys used for prosthesis, and in the aerospace industry [3].

Some of its disadvantages consist of higher initial capital investment for equipment and the fact that the oil-based CLFs are still used. The machine tool should be fitted with high pressure equipment. The system components involve: a high pressure pump supplied with filtered water or emulsion, high pressure pipes or tubes, a nozzle fixed beside a tool holder clamped with adjustable system, and a filtering system. By implementing of this method in the practice, the relatively larger energy consumption (which is compensated by higher removal rates and longer tool life), the noise and emulsion aerosols have to be considered.

Concerning the potential benefits of HPJAM, they refer to the sustainability through lower flow rate of CLF in comparison to conventional machining and the lower cutting forces and longer tool-life. This technique allows an extension of the operational area up to 35% increase in both the maximum achievable feed rate and cutting speed [3, 28]. Other advantages are the significant improvement of chips’ breakability and the increased process productivity by the extension of the machining parameters operational ranges. Unfortunately there is still technological gap concerning the poor investigations of the relationships between the HPJAM process parameters (that act and interact in a complex manner) and the machining performance responses.

3 Evaluation of Technologies’ Sustainability

3.1 Assessment of Machining Process Sustainability

The manufacturing process is isolate from the global sustainability concept. Sustainability studies related to manufacturing processes are based on development of a practically implementable tool as manufacturing process sustainability index through literature survey and experimental work. This can be achieved in different stages starting with characterization. The data collected and the existing modeling capabilities will be used to model the impact of the manufacturing process on the main contributing sustainability parameters.

A complex modeling technique, involving analytical and numerical methods, coupled with empirical data and artificial intelligence techniques, must be
developed in order to quantify scientifically the influence of each parameter. Then, the modeled production process can be optimized to achieve desired level of sustainability with respect to constraints imposed by all involved variables. These optimized results can be used to modify the existing processes and enhance the manufacturing performance with respect to the main factors considered [2].

The optimized results can be finally used in defining the sustainability rating for the specific manufacturing process. For the selected process, the weighing factors can also be used to evaluate and to serve the customized application in establishing the final sustainability rating. Two of the most-needed features of the proposed sustainability assessment systems for machining processes are the user friendliness and communication efficiency.

The main goal in identifying and defining the various elements that contribute to manufacturing process sustainability is to establish a methodology to evaluate the sustainability level of a manufacturing process. Such evaluation can be performed independently of the product life-cycle, recycling, or remanufacturability of the product that is manufactured. Requirements of sustainable manufacturing covering decision-making aspects and recycling are life-cycle assessment, environmental costs, and supply chains [2].

Manufacturing processes are numerous and differ widely, depending on the manufactured product, the fabrication method, and process parameters. Due these considerations, the identification of the factors involved in process sustainability and the demarcation of their boundaries becomes a complex issue.

Processing cost depends also on the method used to produce the part/component and the work piece material selected. In the effort to minimize the manufacturing costs, the industrial organizations endeavor to maintain the product quality, power consumption, and operator and machine safety. In the cases when the processing includes the use of coolants or lubricants and the emission of toxic and harmful materials, this poses environmental, safety, and personnel health problems. Among the various influencing factors, the following interacting factors are relevant to make a manufacturing process sustainable: (1) Manufacturing costs; (2) Environmental impact; (3) Energy consumption; (4) Operational safety and personnel health; (5) Waste management [2].

Within the manufacturing process sustainability assessment only the manufacturing costs involved during the manufacturing operation times, including the tooling costs, are considered. In addition, there are also other direct and indirect costs related to environmental consequences safety aspects and operator’s health. It is needed to count the costs for recycling and reusing of consumables, chips and coolants or lubricants.

Environmental impact contributes to pollution by several basic factors such as resources’ depreciation, chips, metallic dust, use of toxic, combustible and explosive materials, waste of coolants and lubricants and emissions from metal working fluids use.

In manufacturing processes the energy saving for the entire operational period of the machine is one of most needed sustainability factors. The issue consists of monitoring the power consumption rate and evaluating energy efficiency.
Particularly, in the machining processes the power consumption can be decreased by setting optimal cutting conditions, facilitating better tribological conditions, the use of proper lubricants and coolants, the selection of cutting tool inserts and the cutting tool-work piece material combinations. It is clearly that for sustainability assessment of energy/power consumption are preferred the environmentally friendly energy sources. The factor concerning the source of energy can be added in the rating system of process sustainability if the renewable sources are available and widely used in the industry.

Waste management category accounts the recycling and disposal of all wastes resulted during and after the manufacturing process is completed. Even the zero waste generation with no emissions in environment is the ideal process from ecological point of view it is technologically not feasible yet in the practice. Thus the efforts are focused on finding solutions in order to reduce or eliminate wastes.

The operational safety is focused on the ergonomic design of human interface and the possible unsafe interaction between operator and machine during the manufacturing operations. In relation to the manufacturing processes, the safety aspects are generally divided in two categories: personnel safety and work safety.

The last element contributing to the machining process sustainability is the personnel health. Its assessment is based on the compliance with the national and international regulatory requirements imposed to industry, and it concerns the admitted level of emissions and waste from machining operations and their impact on the exposed areas and operators. The personnel health and working area is commonly affected by exposure to the mist and vapors from metal working fluids used as coolants or lubricants during manufacturing processes. These contain usually a large amount of additives in order to enhance the process performance.
At preliminary stage of sustainability evaluation, it is not excluded the consideration of other secondary parameters such as the product’s functionality requirements. They could influence the decision making process being related to energy consumption and machining costs, the marketing strategies and the initial equipment investment. There is a strong interaction between these six main factors even they have different expectation levels [29], as shown in Fig. 6.

Obviously, they can not achieve their best level due to technological reasons and cost implications. A combination of minimum and maximum of factors’ levels will be involved in an optimized practical solution within the constraints imposed.

The analysis of above mentioned factors shows how the sustainability measures can be selected along an appropriate method in order to optimize the machining parameters for a high sustainability.

### 3.2 Assessment Methods

Before starting to use any assessment method, it is important to identify first the boundaries of the system to be examined. Particularly, in the case of machining, the overall system includes activities such as material production, tool preparation, material removal, and cleaning. Figure 7 shows a general machining scenario with the important process stages. The processes included in the diagram will be briefly examined in order to provide a rough estimation of environmental impact. The items marked by grey color have been omitted in the macro-level analysis [3, 4].

The consumption of cutting fluids is one of the critical issues related to environmental impacts of the machining process. It is already recognized that the

![Fig. 7 General machining scenario](image-url)
effect of cutting fluids on the environment, with respect to their degradation and their ultimate disposal, is a major problem. The disposal of cutting fluids at the end of life results into soil and water contamination \[3, 4, 30, 31\]. Also, the cutting fluid that adheres to the metal chips creates a problem for the metal recycling. The metal chips have to go through the waste processing which may include the cleaning, the separation, etc.

The list of the components required for the micro-level comparison between NDM and FM is illustrated in Fig. 8.

This also includes the components (i.e., impact of cutting tools, cutting fluids) which are not present in the macro-level comparison. The higher environmental performance of NDM process to FM process is concluded in macro-level comparison. In order to controvert this relationship in comparison at the micro-level, the environmental impacts of production, the disposal of TiN-coated tools and emissions need to be greater than the summation of environmental impacts shown in macro-level comparison.

### 3.2.1 Material Production

The material production is an important factor to be considered due to its environmental implications. The production of materials is energy- and resource-intensive processes. While material production seems to be outside the system boundaries of machining, the machining can be viewed as a process that pulls in the raw materials, altering them in the course of producing products.

In creating products, the machining process often uses large amounts of material. In many cases, only a fraction of the total material entering into the manufacturing
plant leaves it in the form of a product. The estimations of scrap production in the machining range between 10 and 60% [32].

While these chips and scraps can be recycled, the machining process itself requires the inflow of a large amount of pure material, raw material coming from virgin sources. The consumption of those materials from the virgin sources requires more energy than the use of materials from recycled sources requires only. This is an important process requirement that must be considered when evaluating machining [33, 34]. Thus, the importance of tracing back material flows to material production is obvious.

### 3.2.2 Cutting Fluid Preparation

The cutting fluids are another important part of machining, both in terms of operation and in terms of environmental impact. The most popular type of cutting fluid is soluble oil. In use, soluble oils are typically diluted with water, such that around 95% of the cutting fluid, by volume, is water [4]. The other 5% is a combination of oil, emulsifiers, and additives [35–38]. The additives are used: to limit the corrosion, to control the acidity, to control the microbial growth, to improve the lubricity, and to prevent the foaming.

Given the estimations of the metalworking fluids use along with a work scenario (i.e. 52 work weeks per year, with five work days per week), the values for the amount of concentrated metalworking fluid and water used per machine per day can be obtained. Once formulated, cutting fluids can be circulated through a system numerous times. However, losses frequently occur, often through vaporization or through chips, scrap, and work pieces leaving the material removal process [39]. Some estimations show about 10–30% of the annual total cutting fluid consumption may be lost through these mechanisms [30, 32].

The cutting fluid will pick up contaminants such as metal chips, fines, and tramp oil. Such contaminants can be removed using a separation or filtration process, or the cutting fluid can be disposed of and replaced with fresh fluid. The disposal costs of spent metalworking fluid are approximately equal with the cost of the replacement fluid [40]. In the case of NDM the cutting fluids are completely consumed and, thus all these costs are avoided [41].

### 3.2.3 Tool Preparation

While tooling plays a major role in the machining process, the direct environmental impact of tooling is limited. Due to their relatively long life, the environmental cost of tools and tool maintenance is often amortized over numerous products. This makes their contribution to the environmental impact relatively insignificant in a per machined part analysis. The selection of appropriate tools can allow increasing the material removal rates, thereby reducing the total machining energy required [4].
Currently the most machining processes are done using carbide tools. A large proportion of these carbide tools are sold as indexing inserts, cutting inserts that attach to specially designed tool holders [42].

The carbide tools production does require some energy intensive materials and processes. Some of the manufacturing steps, including sintering (used to form the carbide tool) and physical vapor deposition (PVD) or chemical vapor deposition (CVD) (used to coat the carbide), are also quite energy intensive [43]. The fact that carbide cutting tools can be used numerous times on multiple surfaces means that this energy investment is distributed over numerous parts. Thus, the per part energy contribution from tool production can be more or less ignored, particularly in light of the material removal and material production analyses.

The alternatives to the carbide tools do exist, the most popular being high-speed steel (HSS). The HSSs are still used in the majority of the drilling applications, as well as in many milling applications [44]. Like the carbide tools, the HSS tools can also be coated through PVD or CVD processes. As mentioned earlier, perhaps the biggest difference between high-speed steel tools and carbide tools lies in the machining time [42].

### 3.2.4 Machine Tool Construction

The machine tools clearly play a major role in the machining process, but their direct environmental impact is limited. The most of the machine tools are in use for many years. These long lifetimes mean that the environmental impact of machine tool construction is amortized over numerous products over many years. Thus, the environmental impact per machined part is relatively small. The big effect of machine tools on machining has to do with energy efficiency. The newer machine tools can be significantly more energy-efficient than the older machine tools, resulting in the energy savings during material removal. The efficiency improvements could reduce the energy requirements per unit of material volume removed by approximately 50 % [3, 4].

### 3.2.5 Material Removal

Most of the environmental impact from the material removal process stems from the energy use. In estimating the energy requirements for material removal, the specific cutting energies are often used [4]. While the cutting energies for machining can depend on many factors, including the work piece properties, the presence of cutting fluids, the sharpness of cutting tools, and the process variables, the ranges of approximate cutting energies in machining are available [45]. Determination of specific cutting energies can help to calculate the minimum amount of energy required to machine a certain volume of material.
In the machining processes, in addition to providing energy to the tool tip, additional energy must be provided to auxiliary equipment such as the cutting fluid feeding equipment, the work piece handling equipment, the chips handling equipment, the tool changers, computers, and machine lubrication systems. When the auxiliary equipment is present, the energy needed of the auxiliary equipment can far exceed the actual cutting energy requirements. The energy use per amount of material removed can be estimated by following data [3, 4, 46]:

- **Energy Breakdown** shows how total energy use is distributed among various activities;
- **Constant start-up operations** refer to start-up energy use, such as for computers and unloaded motors;
- **Run-time operations** include energy used to position materials and load tools.
- **Material removal operations** refer to the actual energy involved in the machining.

**Energy Use per 1,000 work hours** can be calculated using: the number of hours spent powered up but idle, the number of hours spent positioning and loading, the number of hours spent actually removing material, the energy required to run the machine while idle, the energy required to run the machine while positioning and loading, and the energy required to run the machine while removing material.

**Material removed per 1,000 work hours** can be obtained by estimating a material removal rate. This estimation is difficult, as material removal rates depend on numerous parameters, including tool material (HSS versus carbide), part material (aluminum versus steel), part design (fine versus rough geometry), and processing parameters (flood versus dry machining).

With energy and material removal data for each machine, the amount of energy required per amount of material removed can be calculated. These values provide a general estimate of the energy requirements for material removal operations in machining. The values should provide a good order-of-magnitude estimate of the energy requirements for the material removal process.

### 3.2.6 Cleaning Process

The cleaning plays also a role in the machining, being one of the most often mentioned when discussing environmental impact. The importance of cleaning, and the environmental impact of cleaning, is highly dependent on the product. By using NDM techniques the cleaning of the products are not necessary anymore. This highly diversified cleaning landscape, both in terms of amount of cleaning and type of cleaning, make general qualitative analysis of this process difficult.

Metal cleaning was dominated by several large-use chemicals that could be used in a wide array of different situations. Currently the numerous different cleaning solutions have been implemented. Many of the new cleaning processes rely on aqueous cleaners instead of solvent cleaners [47, 48].
3.2.7 Environmental Concerns

The analysis of machining presented above, and particularly the analyses of the material removal and material preparation processes, focus heavily on energy use. Energy use and energy sources are important to examine when investigating environmental impacts [4].

While the environmental concerns associated with material removal and material production are focused on energy use, the environmental aspects associated with the cutting fluid preparation and cleaning are more closely to liquid and hazardous waste. These pollutants raise issues at both local and global levels. While some of the chemicals used in these processes can be harmful to workers, such as some additives to cutting fluids, other chemicals are associated with the high-level ozone depletion [4].

4 Conclusion

Sustainable production became a global concept, contenting important elements on all the fields as well as machining processes. Due to the waste and related emissions from the primary processes, metals processing is considered an important source of environmental damages. The way to sustainable manufacturing through environmentally-friendly machining begins from the steps that must be taken to implement ecological machining methods in order to make these technologies reliable, environmentally friendly and cost efficient.

Many elements and aspects of manufacturing processes have important implications for the environment state, but many products can be manufactured by more alternative processes. Often, one of them involves the use of less damaging substances of than the others. The success of sustainable machining methods can be achieved if all components of machining or manufacturing system are suitable for such technologies.

For this, the whole processes and all aspects and elements involved have to be considered. First of all, a machine tool (manufacturing cell, production line etc.) and cutting tools should be specifically designed. Although some machine tools have been retrofitted, this solution does not appear to be an attractive alternative. Ideally, the consideration of ecological aspects in the area of machining starts from the part design. This should make the process easier in terms of chip removal (evacuation) and process performance.

Studies in this area are focused on process level activities and improvements. These improvements, including minimizing the use of cutting fluids (coolants or lubricants), optimizing material use, appropriate treatment of contaminated parts and chips and reducing cutting energy, do have important environmental links.

For example, metal working fluids have become more problematic in terms of both workers health and environmental pollution, with serious issues resulting from their use, treatment and disposal, are often analyzed as a problem for
potential improvement. Beside ecological aspects, due to the high disposal costs, manufacturers are self-motivated to reuse products, reduce and/or eliminate waste, but they need alternative technologies from which to choose the best solution. Such processes and facilities must minimize flows and environmental loads wherever possible.

The overall sustainability level of the machining process is to be evaluated. The existing and new proposed process sustainability assessment methods should be used in order to involve science-based sustainability principles, not only for product manufacture but also for its design. In this respect it reveals the need for identifying relevant sustainability indicators and for developing methodologies for quantification of influence factors using modeling and optimization methods.

**Abbreviations**

CLF Cooling lubrication fluids  
CM Cryogenic machining  
DM Dry machining  
HPJAM High pressure jet assisted machining  
HSS High speed steel  
LN Liquid nitrogen  
NDM Near dry machining  
MQL Minimal quantity lubrication  
MQC Minimal quantity cooling

**References**