A Review of Sustainable Machining Engineering: Optimization Process Through Triple Bottom Line

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The studies about sustainable manufacturing engineering (SME) contain an increasing body of knowledge, motivated by the rising interest in the processes lifecycle sustainability. Its continuous improvement and optimization (including sustainability criteria) has become an emerging necessity. For this reason, new clean technologies and proposals of work methods are required; they have to integrate the ecological and social dimensions at an operational level in the manufacturing processes, maintaining the economic and technical feasibility attained up to this moment. However, a unified framework does not exist to orientate the lines of research in optimization when applied to sustainability. In this sense, the article reviews studies from scientific literature about sustainable machining developed in the last 15 years. The review has been carried out from the triple bottom-line (TBL) perspective, defined by the three general sustainability dimensions (economy, ecology, and equity). It contributes to the literature and current machining engineering knowledge, with its involvement in mitigating the metabolic rift. The results from the review have allowed to characterize the investigation effort, with regard to the optimization of the sustainable machining processes; even though numerous studies exist which optimize machining operations (with the aim to find the trade-off between different environmental and equity factors), in general, the technical and economic feasibilities are still the priority. The patterns defined through the analysis of the publications have established the current development trend; furthermore, as a consequence of the review results, we propose an outline of articulated lines of investigation with the aim to mitigate the metabolic rift through triple bottom-line, necessary so that machining engineering assumes the goal of finding the balance to achieve integral sustainability.
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1 Introduction

The constant adaptation of manufacturing engineering to the products' growing needs, services, and industrial systems demanded by society has provoked in the last century a great impact on the planet, contributing to the increase in the metabolic rift [1,2]. This term was coined by Marx [1] to name the effects of the capitalist system over the metabolic interaction (exchange of matter) between nature and society in a linear or scarcity economy (see Fig. 1).

The metabolic rift represents the alienation of earth from society. It corresponds with the existing distance between the natural capital (provided by the planet) and the social capital; it is also defined by the consumption of energy resources and materials (necessary to cover the inputs and outputs, needed in the production chains, and the corresponding impacts—damages, diseases, destruction of biodiversity, resource depletion, changes in ecosystems, etc.) caused by the humans' economic activities.

The mitigation of the metabolic rift is the origin of the current framework that is used to structure and manage sustainable manufacturing (SM) from the three dimensions known as: economic capital—economy, environmental capital—ecology and human capital—equity. They interact as a whole and in a fractalized manner, establishing the triple bottom line (TBL or 3E) [3] to achieve three objectives: (1) improve the economic, environmental and human performance, simultaneously; (2) reintegrate the antrophospheric and natural ecosystems; and (3) mitigate the metabolic rift. The first approximations toward sustainable development (with the metabolic rift) and the evolution of the concept toward 3E have established the currently accepted definition of sustainability: *sustainable development is the development that meets the needs of the present, without compromising the ability of future generations, to meet their own needs* [4].

For machining engineering, this framework has evolved through a series of stages that are synthesized as follows: first, with an approach orientated exclusively toward economic results with technological feasibility. Second, integrating in the previous approach, efficiency improvements of the energetic, environmental, and functional kind. Finally, with an integral approach where

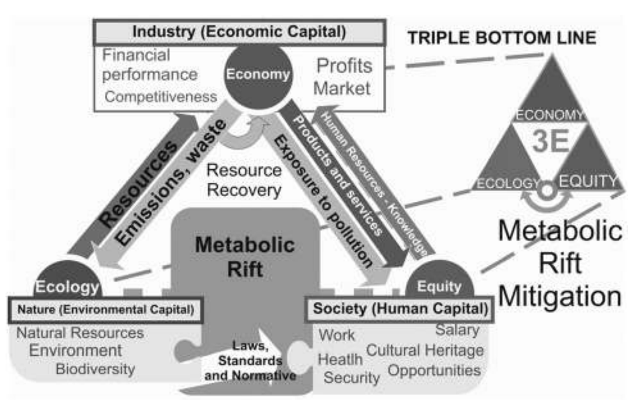

Fig. 1 Metabolic rift and TBL frameworks

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equality and the search for balanced results in the three dimensions are taken into consideration.

The interest that manufacturing engineering has had during its historic evolution, regarding the continuous improvement, has motivated the development of new clean machining processes which are orientated to mitigate the metabolic rift. The optimization process (OP) is of great interest to the continuous improvement of sustainability [5,6]; it will reduce the environmental and social impacts, maintaining the results' technical and economic feasibilities and promoting future economic opportunities. It also facilitates the gradual incorporation of improvements: from the early stages of the design and development of the processes, up until its operation execution in the stages of implementation, exploitation, and retirement in real environments.

All of the above motivates carrying out a comprehensive review of the existing scientific literature; this review has the intention of evaluating the condition and tendencies of the investigation lines that are destined to optimize sustainable machining. The aim is to gather the main challenges that the scientific and technical community have to assume in order to address machining sustainability and to revert the metabolic rift from a triple value (economic, social, and environmental).

2 Research Methodology and Scope of Study Definition

A status quo review will be carried out. This is a critical analysis of the available literature in the specific field of optimizing sustainable machining engineering. The latest publications are analyzed with the aim of identifying the research effort and its patterns and trends; these allow to describe the areas of work developed and other research areas that are not taken into consideration in the optimization of sustainable machining processes.

The selection of the study level for the review is shown in Fig. 2; on the left side are the stages that are generally involved in the product lifecycle (material extraction and processing, manufacturing, logistic, use, inverse logistic, and end of life). The manufacturing stage includes the set of activities and operations which (through production processes) convert the material and energy inputs into products and services [7]; it can be divided into the levels: macro (supply chain), meso (factory), and micro (processes). The microlevel includes the set of operations associated to the manufacturing processes within the three categories [8,9]: subtractive processes (such as milling, turning, drilling, or grinding), additive processes (such as joining or coating), and mass-conserving processes (such as forging or bending).

The review's interest is focused on studying the optimization of the subtractive processes (by the volume of waste, toxicity, and other important parameters, like energy or material consumption); in particular in the improvement of the sustainable machining processes, including conventional machining (turning, milling, grinding, or drilling) and nonconventional machining (laser beam, water jet or electro chemical between others).

Other reviews of interest exist that study the state of the art of machining or sustainable manufacturing (for example, Refs. [10–12]). In this case, it is considered to be necessary to develop the state of the art taking into consideration a complete variety of parameters and aspects that orientate the optimization process toward balance in the three dimensions. It is an opportunity for sustainable development in machining.

The research process carried out in this paper can be reproduced using the keywords listed in Table 1; they have been compiled from Refs. [13–15] where different sustainable indicators, both generic and focused on sustainable machining, are analyzed.

These words were organized in five key areas that include different levels conforming to the study objectives; the controlled vocabulary (thesaurus) used for the indexing process of the scientific articles in the major search engines and databases has been collected; so, it has been selected: EiCompendex, EIT Inspec, Geobase, SciELO Citation Index or Present ISI Proceedings-Science and Technology.

For the selection, classification, and assessment of all the works published, more than 300 scientific papers have been analyzed, of which 170 have been selected using the following two criteria: (A) *Time criterion* (papers published between 2000 and 2015) and (B) sustainable dimension (e.g., the scope of the study taking into consideration the 3E framework which will characterize the investigation effort).

The optimization studies selected are publications that introduce development methods, tools, and case studies, with the aim to obtain an optimum solution; in addition, some of the studies complete their purpose by proposing approaches, strategies, and improvement proposals.

As shown in Fig. 3, the review is organized as follows: Sec. 3 emphasizes the optimization process and describes the key types and available methods for the machining engineering (Sec. 3.1). The next sections evaluate the research effort through the 3E perspective: In Sec. 3.2, 3E integrated works are analyzed; Sec. 3.3 investigates the economic dimension (EC); Sec. 3.4 evaluates the ecology dimension; and Sec. 3.5 summarizes the equity dimension (EQY). Later, in Sec. 4, the research effort is characterized with the following aims: (1) to establish tendency patterns and (2) to orientate the future lines of study to find the required balance to reach integral sustainability in machining. Finally, in Sec. 5, the insight and future research are proposed.

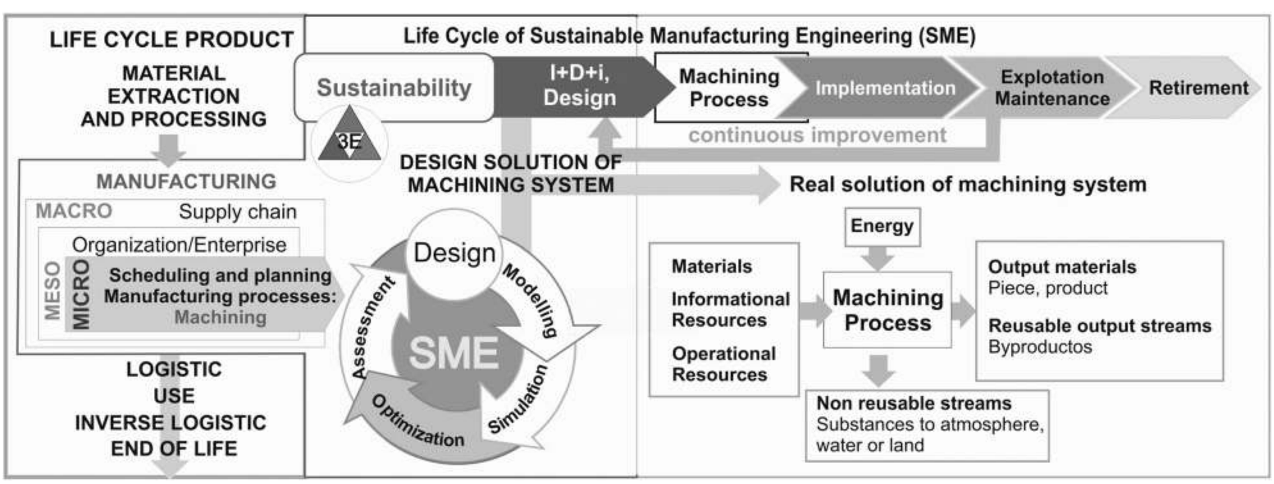

Fig. 2 SME, microlevel for sustainable machining

Table 1 Key areas to lead and reproduce the review

KEY 1. APPLICATION AREA		KEY 2. ECONOMIC DIMENSION	KEY 3. ENVIRONMENT DIMENSION	KEY 4. SOCIAL DIMENSION	KEY 5. RESULTS
Manufacturing Paradigms	**Optimization**	**Input/Output**	**Input/Output**	**Input/Output**	Efficience
Sustainable Manufacturing	Annealing	Control Parameters	Environmental inventory	Cognitive task	Job Flow Management
Cleaner production	Finite Element	Cost and investment	Greenhouse gases	Ergonomics and Human Factors	New& Innovation
Green manufacturing	Genetic	Cutting condition	Material Removal	Feedback Machine (information task)	Performance
Environmental Concisiuos	Minimization	Information Management	Resources Consumption:	Human behaviour	Productivity
	Multi-objective	Laws & Standars	Coolant	Kansei Engineering (psychological	Reliability
Machining Processes	Neural network	Machine learning	Energy	Multi-response	Scheduling
Turning	Tabu	Resources Cost	Fluids	Semantic	Surface
Milling	**Triple Bottom Line Framework**	Fluids	Raw Material	Skills (worker)	
Drilling	Ecological	Energy	Water	Special Population	
Grinding	Economic	Water	Substance emissions	Training	
EDM (electrical discharge machining)	Equity	Raw Material	Waste streams	Workplace	
Facing	Environment	Coolant	**Impact/Damage**	**Impact/Damage**	
Planing	Social	Tool	Carbon Footprint	Accident	
Broaching	Green	Time	Ecologic Footprint	Comfort/Discomfort	
Shaping		**Impact/Damage**	Environmental Impact	Risk	
Hybrid Process		Competitiveness	Hydric Footprint	Safety & Health	
		Profits	Toxicity	Well-Being	
		Quality assurance			
		Local economy			

3 Optimization Processes in Sustainable Machining Engineering

Optimization includes a set of continuous improvement activities that can offer the best solution by adjusting one or more parameters (affecting the behavior thereof); these patterns are obtained by modeling and simulating a complex system. This implies the search of the tradeoff between the different factors (that characterize a complex problem) with the aim of reaching the desired results [16]. With regard to sustainable machining operations [17], any parameter relevant to the process can be selected for efficiency improvement (economic, environmental, or social performance); it will be necessary to select them adequately and limit the solution scope, since improvement in any of the three sustainable dimensions can affect the other two, negatively or positively.

3.1 Available Optimization Approaches in Machining. In the literature, an elevated number of publications exist, relating to the optimization of the machining process. From the first studies carried out by Taylor regarding the tool's life [18,19], the set of work lines have experienced an ample growth and a wide variety

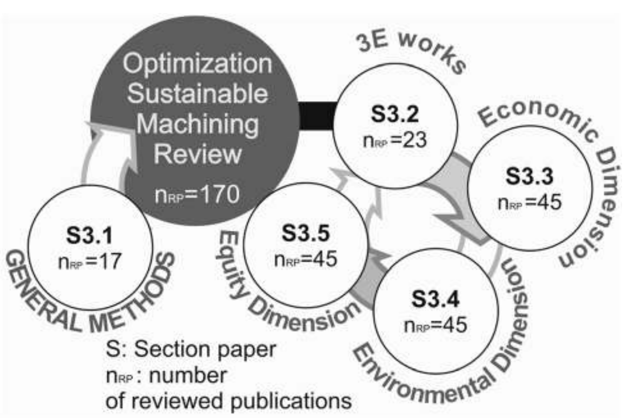

Fig. 3 Review structure

of optimization techniques are used nowadays [17,19,20]: from traditional mathematic methods (linear and nonlinear programing, dynamic programing, Lagrangian multipliers or finite elements [21]) to new techniques that have been developed to solve previous limitations. These new techniques are statistical methods (*like ANOVA* [22], *statistical regression* [23], *fuzzy set theory* [24], *Taguchi method* [25], *or response surface-design methodology* [26,27]) and Nontraditional Algorithms; the latter consist of heuristics and metaheuristics, for example, *search strategies* (*simulated annealing* [28], *Tabu search* [29], *or scatter search* [30]) or bio-inspired algorithms, for example, *artificial neural networks* [31,32], *naturally inspired algorithms* [33], *or evolutionary algorithms as genetic algorithm* (GA) [34,35].

In general, the optimization of sustainable manufacturing (SM) implies solving complex multi-objective and multicriteria problems [17]; this is the reason why traditional techniques (in many situations) do not reach the specific requirements for sustainable improvement. On other occasions, the design, modeling, and simulation phases are not available for the machining process. It is also possible that the classical optimization procedure is not applicable; this is a frequent situation in some areas of sustainability that have a small research trajectory: for example, the optimization of social or environmental variables. In this case, the optimization techniques are ad hoc proposed and many of them are in the initial phase of development (in its descriptive and qualitative form).

A set of studies exist which analyze different optimization techniques applied to machining; in them, the knowledge base, applications, and functionality are described from the conventional point of view (economic) or including parameters from the ecological and equity dimension. In Refs. [16], [19], and [36–39], the best available techniques for the machining optimization are collected; they are later selected by other authors to achieve the sustainable improvements and proposals. The studies of Jawahir et al. [40,41] should be highlighted, where sustainability is presented as a driver of innovation and where the current machining challenges can be consulted in the 3E framework; the authors bring a general vision of the product and process with regard to the recent tendencies, new concepts, prediction methods, and optimization procedures. Also, in Ref. [42] Peng et al. gathered a set of models, methodologies, and optimization techniques applied to machining systems, from the following point of view: energy efficiency, process planning, and production programing. The optimization techniques are grouped in four categories: theoretical, empirical, discrete event-based, and hybrid models.

With regard to the election of the optimization objective, multiple parameters are selected like process planning and scheduling, productivity, tool life, machining process parameters (MPPs), environmental-economic-social efficiency, costs, surface finish, or toxicity of emissions.

The study's interest for technical viability and cost reduction, has provoked an imbalance in the research lines in sustainable machining, being the economical dimension the most valued, followed by the ecological and the equity. For these reasons, in the next sections the current structure of the research effort will be analyzed; it is carried out by reviewing a set of studies, organized according to their main scope: Sec. 3.2 integrated optimization with 3E, Sec. 3.3 economic optimization (economic dimension), Sec. 3.4 environmental optimization (ecology dimension), and Sec. 3.5 social optimization (equity dimension). These last three sections include studies whose prime aim is focussed on the dimension that they belong to; however, in the optimization process, they generally consider some parameters that balance the results in the other two dimensions.

3.2 Integrated Optimization of Sustainable Machining From the 3E. Sustainability is a concept essentially dynamic and multidimensional. Its origin has to part from a value system, defined in a set of objectives which are associated to the three fundamental dimensions: *economical* (referred to cost-effectiveness, technical viability, and future business opportunities), *ecological* (compatibility of the activities with the environment and its cycles), and *equity* (attention to quality of life and human, individual or collective well-being) [3]. The dimensions interact dynamically in the process to find solutions, which means a triple account of eco-innovation results. This vision is achieved through the life cycle thinking strategy [43,44]; when it is applied to products, processes, or services, it implies a constant redefinition, making the system evolve toward total sustainability due to a continuous improvement process (Deming circle of plan-do-check-act).

In a business context, this idea derives in an operational framework named *life cycle management* [45,46]; this integrates the management systems of the occupational, environmental, and quality areas (Fig. 4) under the 3E. The first backed up by OHSAS-18001 (Occupational Health and Safety Assessment Series) materializes the social dimension strategy through the company's Social Responsibility, and occupational health and safety; the second, the ISO-14000 series, is an international environmental management standard that makes the environmental dimension (ENV) operational and effective, and finally the ISO-9000 series allows quality management and structures the economic dimension [47].

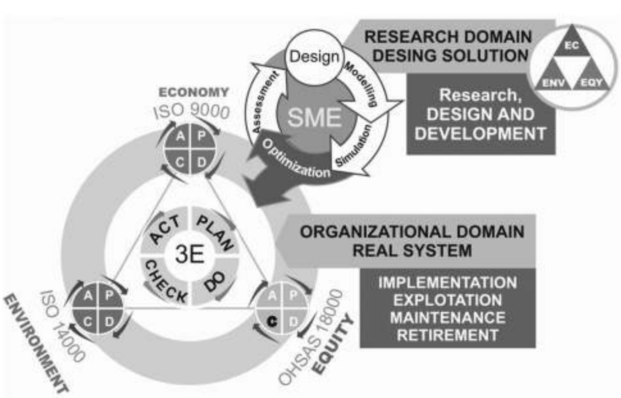

Fig. 4 Sustainable research and industrial domain

This perspective [43–46] provides sustainability with a multidimensional and complex character, entailing the satisfaction of several simultaneous targets many of which can be totally or partially conflicting: improvements in one dimension can impair the rest. To find a balance between them, an optimization process is essential; it is able to define priorities, select and adjust the goals, needs, or requirements and once the results are achieved, verify its integration and scope. Furthermore, it allows the incorporation of gradual and continuous improvements in the process serving as nexus between the corporate and investigation areas.

In general, the publications about sustainable machining based on the 3E are not abundant. The existing ones are backed by the goals of the paradigms cleaner production (CP) [48–51] and green manufacturing (GM) [52–56], and the majority focus on the knowledge development or the methodological proposal; they have a descriptive and qualitative focus and they analyze the possible optimization parameters and future keys for the investigation. This is the case of Byggeth et al. [57], who proposed a set of basic ideas for an optimization process, with the technical evaluation of machining and sustainability; it can introduce socio-ecological requirements in the design and in the properties of the machine tool, illustrating the case study in a water jet cutting process; the proposal can be used to identify feasible long term investments and new business opportunities. Xu and Liu [58] evaluated the machining process plan from GM and the necessary methods for its optimization; they studied each variable (routes, methods, equipment, process parameters and programs) and its contribution in the improvement of the environmental, economic, and social performance.

On the other hand, due to this knowledge development in sustainable manufacturing engineering (SME), new lines of study from a systematic and analytic perspective arise with more frequency; this is to say, that it takes into consideration the improvements in each of the architectural elements of the process, inputs and outputs, like its sustainable global behavior. This is the case of machine-tool optimization; the efforts are focused in knowing the design requirements to improve the 3E efficiency of the process, through the development of optimization models for decision making; for example, Avram et al. [59] developed *Global Reasoning for Ecoevaluation of Machining*, a multicriteria decision method under GM and software; this method allows the selection of the best machining strategy, taking into account 3E parameters at system level (productivity, cost, precision, flexibility, power energy and emissions) and process level (tool life, time, surface roughness, cutting force, cutting fluid, air quality, and cutting power). The authors illustrate its application in milling. Or the proposal of Tan et al. [60], with a multi-objective optimization model, for the selection of fluids under GM, assuring quality (maximization), cost (minimization), and environmental impact results (minimization, divided into ecological impact, occupational health, safety, and sanitation management).

Also, noteworthy, are the new technology proposals which improve the machine tool in the three dimensions. This is the case of *Microflood technology* [61] which permits direct contact between the cutting tool and the fluid, without the interaction of a gaseous medium, to minimize the consumption, the toxicity in the environment, and increase occupational health; minimum quantity of lubricant (MQL) [62] minimizes the energy consumption, waste stream, and floor space, increasing the process' flexibility and creating a healthy and clean environment for the worker; or the *microfiltration of fluids systems* designed to reduce the biological risk (including health and environmental risks). Emphasizing the studies of Skerlos and Zhao [63], they minimize the cost of this technology and analyze the optimal system operation schedules.

3.3 Optimization of Economic Dimension. The economic dimension [64] refers to the set of activities and operations that orientate the business targets and strategies in a profitable form;

this is carried out through economic efficiency, maintaining the technical feasibility, assuring the quality of the results, the impulse to grow and the creation of new business opportunities orientated toward innovation and continuous improvement [65]. This dimension creates the necessary relationships between the social groups and economic sectors, in charge of making available to the clients and consumers, a set of products and services that satisfy the human needs; this requires an efficient demand management process, which is carried out by the company, starting with the creation of an added competitive value in the form of quality goods and services [66]. Although it has been developed, the economic dimension has witnessed how its priorities have changed in the last decades. Since the second half of the 20th century, its exclusive focus toward economic capital development has been restructured. The social capital and natural care have been included as priorities in the effort to reduce the metabolic rift [2].

With regard to the economic dimension applied in the development of sustainable machining processes, the areas of research and development include the set of "conventional" factors; this is to say, those parameters that have maintained an ongoing improvement and evolution in the machining processes since the Industrial Revolution: time, cost and quality. In this section, the optimization and improvement processes of the economic dimension in machining are analyzed (Fig. 4) taking into account the six study aspects: Planning and scheduling (Sec. 3.3.1), productivity (Sec. 3.3.2), quality assurance (Sec. 3.3.3), profitability (Sec. 3.3.4), machining environment (Sec. 3.3.5), and specific material machining (Sec. 3.3.6).

3.3.1 Planning and Scheduling Programing. The planning and programing of machining is of great importance to sustainability optimization. There are a number of studies dedicated to optimizing the different technological areas of the process, however individually (tool, process parameters, machine setup, energy consumption or biodegradable working fluids); without an integration at meso level (factory), where the planning, programing, and optimum sequence of production flow is determined, the improvements in the individual processes will be useless (reaching local optimums). (1) *interoperability,* (2) *connectivity,* (3) *workflow coordination,* (4) *adaptability and flexibility to dynamic workflow, and* (5) *standardization and complexity reduction in the exchange of information* are essential characteristics for improving the sustainability of the machining shop floors; in this way, sustainability is orientated toward the search of global optimums of the manufacturing system [67–69]. In this line of study, Gong et al. [70] proposed an algorithm using Finite State Machines, Mixed-Integer Linear Programing and Genetic Algorithm to determine the best job-sequence. Thanks to the creation of an energy-cost-effective schedule, the following parameters are minimized: energy consumption, cost, and greenhouse gases during the peak period; this process is implemented in grinding. Finally, Zhao et al. [71] developed the GPIT method for the workshop layout and machining operations based on GM; green planning and optimal operation are carried out, minimizing the resource consumption impacts, the environmental impacts, optimizing the performance of the shop floor, and taking into consideration the economic benefits.

3.3.2 Productivity and Sustainable Performance. With regard to productivity optimization, strategies and new technologies are studied with the aim of improving. These strategies can increase the sustainable performance, reduce the environmental burden, and maintain the technical and economic feasibility of the results; this is to say, that the productivity and the machining performance are evaluated using metrics like *dimensional accuracy, time and availability, service life, cost, tool-life, tool performance, workpiece quality*, controlled by the *cutting forces, surface roughness, or tool-wear* [72] and with the process parameters (spindle speed, feed rate, cutting depth, among others). The studies of Sharma et al. [73] and Lanza et al. [74] stand out; Sharma et al. [73] present different options in cooling techniques (minimum quantity lubrication (MQL) and near dry machining (NDM), high pressure coolant (HPC), cryogenic cooling, compressed air cooling and use of solid lubricants/coolants) to increase the productivity and reduce the environmental burden in turning; Lanza et al. [74] maximized the reliability of the machines components by calculating time and the optimum number of intervals for preventive maintenance. There are other studies about the increase in the productivity in sustainable machining processes; for example, in wire-cut electrical discharge machine [75], in turning [76], in water jet cutting machine [36,77], or in the milling process of heavy-duty computer numerical control (CNC) machine tools [78].

3.3.3 Quality Assurance. The studies concerning superficial quality are addressed to ensure the final results and functional performance in the machining processes; in general, quality is taken as a constraint in the optimization of another parameter (for example, reduction times, cost, energy consumption, or change to ecological working fluids [79]). For example, the modifications which intend to establish improvements in the environmental or social dimensions are optimized so that their implementation does not reduce the quality of the results; highlighted in this field of optimization, surface roughness is the metric that is selected most frequently to determine the tradeoff between the different sustainable improvement parameters [80]. Kant and Sangwan [81] provided a prediction and optimization of an MPP model to reduce energy consumption and ensure the superficial roughness. Other studies of interest are the following: Corso et al. [82] who optimized machining time by maintaining constant the quality of the results and comparing *Sequential Quadratic Programing optimization*, *Genetic Algorithms, and Simulated Annealing*; Yan and Li [83] carried out a multi-objective optimization of the milling MPP, trying to find the trade-off between energy, production rate, and cutting quality; and Cus and Balic [34] determined the optimum MPP using Genetic Algorithm, by improving the cutting conditions, minimizing the time and cost, and ensuring the superficial quality; the authors illustrate the proposal with cast steel turning.

3.3.4 Profitability: Investment and Operating Costs. With regard to cost optimization, the studies examine the profitability when new clean technology is incorporated or when the existing processes are adjusted or changed. The search for the balance between investment, economic feasibility, operational costs, or environmental benefits in the machine tool's life cycle is the line of study most developed.

Gontarz et al. [84] proposed a methodology to determine adequate investments, with an economical evaluation of the improvement solutions to introduce (Retrofit and refurbishment activities), taking into account the resource consumption and the efficiency increase of the machine tool. Branker et al. [95] created a microeconomic model that includes an estimation of the environmental costs to optimize the MPP (from an environmental point of view) and reduced the financial risk. Jin et al. [24] proposed two optimization models (Fuzzy Optimization Model and Multi-Objective Nonlinear Programing Model) for planning processes to minimize cost, time, and environmental impact factors. Schultheiss et al. [96] studied the possibilities of reducing cost with lean manufacturing strategies.

Other important articles are the ones related to the proposal of methodologies to find the balance between costs and sustainability; Narita [87] used the material flow cost accounting (method standardized in 2011 in the regulation EN ISO 14051:2011) to calculate the best cutting conditions; the study minimizes the cost and the environmental burden, based on the technique activity-based costing (ABC) applied to the electric consumption of a machine tool, coolant, lubricant oil, cutting tool, and metal chip; the case is illustrated in a vertical machining center. Yoon et al. [88] studied the conflict between energy minimization and cost minimization, and Helu et al. [89] evaluated the tradeoffs between sustainability, performance, and cost of GM.

3.3.5 Machining Environment. In the machining environment field, understanding this to be the set of elements that structure the process' architecture (machine tool, auxiliary equipment, inputs and outputs), the most frequent proposals combine the following aspects: (1) the improvement of the machine's efficiency, (2) the reduction of the environmental burden by using the cutting tool (increase of the life cycle and minimizing the switching rate), and (3) the improvement of the tribological aspects.

Schultheiss et al. [90] proposed an alternative method of production cycles, for milling and turning, which maximizes the tool use, minimizes the environmental impact, maintains the quality, and decreases the production cycle time by 15%. Ojha and Dixit [91] studied the management and improvement of the tool in turning, estimating the useful life through neural networks and multiple regressions. Kaminski and Alvelid [92] maximized the cutting tools life cycle with the technology high- and ultrahigh-pressure water jet.

3.3.6 Performance of Specific Material Machining. Focusing on metal machining, the research effort includes (1) the study of the process when new technology and sustainable strategies are introduced, (2) the evaluation of its influence on the quality of the results, and (3) the synthesis of the resulting sustainable performance (input of resources, energy consumption, time, use of lubricant-coolant, emissions, or waste streams).

From an analytical point of view, Neugebauer et al. [93] presented various examples of machining processes and technological options, for the metal cutting industry: elimination and substitution of process steps, reduction of the base time, hybrid processes, cooling strategies, and optimization of friction and wear; once these are optimized, they are more efficient in cost, superficial quality, and environmental aspects (like energy consumption and resource use). Welf-Guntram et al. [94] propose High speed cutting and high-performance cutting processes, as a way, to optimize and improve, both resources and energy efficiency in the machining processes.

A wide variety of studies exist concerning the adaptation of the clean processes to different materials; the results of the sustainable machining process applied to particular materials are analyzed. For example, Boswell et al. [95] studied the machining of Boron Carbide Particle Reinforced Aluminum Alloy (AMC220bc), widely used in the aerospace industry due to its low thermal conductivity causing a high temperature in the processes interface (reducing the tool's life cycle); the authors determine the optimum MPP for sustainable machining using Pareto ANOVA and Taguchi Method.

Other examples worth highlighting in this field are summarized in Table 2. The publications aim at optimizing the machining process of specific materials.

3.4 Optimization of the Environmental Dimension. The environmental dimension [65] aims to integrate contexts, this is to say, that the antrophospheric (industrial, urban, rural) and natural ecosystems are in balance and coexist with positive interdependence [64,65]. The industry must achieve a responsible relationship with the planet, by maintaining the needs and the desired social, cultural and economic growth; it is necessary to share resources, respect the natural cycles, and contribute value to the environment (the activity outputs should contribute positively and not pose an environmental impact) [109]. This is, the reinstatement of the human being, in the natural environment [2].

By managing the process' inputs and outputs at machining level, the solutions can be orientated to reduce and eliminate the environmental burden. In particular, inputs management is possible with responsible use, rational consumption, and recycling (closed-loop material cycle, reduction of water use, energy and raw materials). With regard to the outputs (product, reusable and nonreusable streams), these are controlled by a (1) cleaner production, (2) waste and industrial metabolism management, (3) eco-efficiency, and (4) contamination prevention for the care of the abiotic elements (water, atmosphere, and soil) [66,110]. In this section, the optimization and improvement process of the environmental dimension in machining is analyzed taking into account the three study aspects: Energy, cutting fluids, and innovation and cleaner machining process.

3.4.1 Energy. Energy is currently one of the main topics in the investigation of sustainable machining processes, because manufacturing is being one of the energy-intensive industrial sectors [70,111]. There are many *energy efficiency* studies and they focus on selecting the optimum MPP (that reduce the energy consumption); some also include improvements in other environmental aspects, such as *environmental burden* (measured by different impact categories according to life cycle assessment methodology), *greenhouse gases* [112], *exergetic efficiency,* or parameters from the *economic dimension* (quality, time, and cost). In general, the publications that focus on energy efficiency, study parallel to this, technical feasibility, economic impact, and the possible environmental benefits [113].

There are numerous studies which optimize the MPP of particular machining operations, under minimum energy conditions and achieve tradeoff with other factors (maintaining the technical and economic feasibility). For example, Campatelli et al. [27] use Response Surface Method for milling and dry lubrication; Arif et al. [114] posed a model using nonlinear programing to select the MPP under GM in a multipass turning operation; or Aggarwal et al. [96] who used Response Surface Methodology and Taguchi's technique, applied to CNC turning with Cryogenic cooling.

From the machine tool's point of view, energy efficiency can be optimized by studying its behavior in a holistic form; this is, taking into account an energy *consumption profile* with which the energy footprint can be evaluated afterward. For example, Bi and Wang [115] developed an analytical SM model to learn about the relationship between the MPP and the energy consumption; the authors proposed a modeling method based on the kinematic and dynamic behaviors of machine tools. It is illustrated in drilling.

To reduce the energy footprint, the consumption profile should be as complete as possible; it will be defined by the type of process, the machining parameters, and the static and dynamic operating stages, this is to say, differentiating between *basic power* (it covers the required energy, till the machine is ready for the operation period), and *specific process power* (required for machining the piece) [116]. It is also necessary to consider the structure and components of the machine, the process' set of inputs and outputs (work fluid, raw material, compressed air, etc.) and the auxiliary equipment (supply, filter systems, etc.). Other authors include the energy embodied of tooling material; this is defined as the energy needed to produce a cutting tool or a workpiece material. In accordance with the above, for example, the energy profile of a turning operation will be calculated from the sum of the energy consumption variables of E1 (setup operation), E2 (cutting), E3 (tool change), E4 (energy embodied in cutting tool), and E5 (energy embodied in workpiece) [117].

Different models are used to reduce the footprint completely; they evaluate the machine tool's behavior and configure the adequate MPP. For example, the proposal of Mativenga et al. [117,118]: a calculation model that adjusts the MPP minimizing the energy footprint; furthermore, the authors explore the conflict and synergy between minimum cost and minimum energy, and illustrate the study in the dry turning process, including the energy embodied in the tool in the energy profile. Emphasizing the publication of He et al. [119] who minimized energy taking into account the selection of the machining tool and the operational sequence in the flexible job shops.

A key aspect for evaluating and improving the process' behavior is monitoring in real time. This is possible by controlling production processes and studying the electrical demand, which will select in situ, the optimum MPP according to the process' energy demand [120]. In this area, O'Driscoll et al. [121] developed a *nonintrusive intelligent energy sensor* that monitors the process in real time. This element is able to achieve relevant information and adjust the function to improve the machine tool's energy efficiency.

One of the emerging lines is to measure energy efficiency with exergetic loss. Exergy is understood as "the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the abovementioned components of nature" [9,122]; it is one of the indicators that can be used to optimize the machining process' sustainability (raw materials, energy, or emissions) [123,124]. An analysis and exergetic optimization [125] take into account both energy and material flows; also, by including the concept of energy usefulness, it is possible to differentiate between useful and useless energy in the process' energy profile [125].

Table 2 Performance of specific material machining

Publication	Optimization method	Material machined	Machining process	Parameters optimized
Abhang and Hameedullah [26]	RSM	EN-31 steel	Turning	Power consumption and productivity
Aggarwal et al. [96]	Taguchi	AISI P-20	Turning	Power consumption
Bhattacharya et al. [97]	Taguchi design and ANOVA	AISI 1045 steel	High speed machining, with dry machining	Surface finish and power consumption
Bhushan [98]	RSM, design of experiments	7075 Aluminum alloy	CNC turning	Power consumption and tool life
Biček et al. [99]	Taguchi	AISI 52100 bearing steel	Cryogenic machining, turning	Tool lifetime, residual stresses and surface integrity
Boswell et al. [95]	Taguchi method, ANOVA	AMC220bc (boron carbide particle reinforced Al alloy)	Milling	Carbon footprint
Camposeco-negrete [100]	Taguchi methodology and ANOVA	AISI 6061 T6	Turning	Energy consumption and surface roughness
Davoodi and Tazehkandi [101]	RSM and ANOVA	Aluminum alloy 5083	Dry and wet machining, turning	Tool tip temperature, chip thickness, machining parameters
Dhar et al. [102]	Finite element	AISI 1040 and E4340C steel	Cryogenic cooling in turning	Tool wear, dimensional accuracy and surface finish
Dhar et al. [103]	RSM	AISI 1040 and AISI 4320 steels	Cryogenic cooling by liquid nitrogen in turning	Chips and cutting forces
Eker et al. [22]	Taguchi, signal-to-noise and ANOVA	Magnesium alloy materials	Turning with MQL	Lubrication, surface roughness and temperature
Fratila and Caizar [25]	Taguchi method	AlMg3	Face milling	Lubrication, surface roughness and power consumption
Garg and Lam [20]	Multigene genetic programing	AISI 1045 steel and 7075 Al alloy	Turning	Surface roughness, tool life and power consumption
Joshi [17]	Exhaustive enumeration-search algorithm	Powder metal steels	Boring and plunge cutting	Tool life, tool wear and cutting conditions
Jozic et al. [104]	Taguchi and Grey relational analysis	Steel 42CrMo4	Milling	Removed material, surface roughness, flank wear and cutting force
Koyee et al. [105]	RSM; cuckoo search	Duplex stainless steels	Turning	Cutting parameters, cutting fluids and axial length of cuts
Ma et al. [106]	Finite element	AISI 1045 steel	Dry machining	Performance of micro-grooved cutting tools and energy
Pusavec et al. [6]	Genetic algorithms (GAs)	Nickel alloy—Inconel 718	High performance machining; dry, near-dry (MQL), cryogenic and cryolubrication (cryogenic + near-dry)	Environmental impact, energy consumption, safety, personal health, waste management and cost
Pusavec et al. [107]	RSM, ANOVA	Nickel alloy—Inconel 718	High performance machining; dry, near-dry (MQL), cryogenic and cryolubrication (cryogenic + near-dry)	Cooling-lubrication and machining performance (cutting forces, power consumption, tool-life and productivity)
Sharma et al. [73]	FEA techniques	Different AISI—steel	Turning with MQL, NDM, HPC, cryogenic, compressed air cooling and solid lubricants	Tool life, surface finish, conductivity, chemical degradation
Winter et al. [108]	Mathematical optimization	Hardened carbon alloy steel (62 HRC)	Grinding	Energy consumption, cutting fluid, kg CO_2 eq and cost

3.4.2 Cutting Fluids. In the last years, the interest in sustainable machining has reinforced the development of environmentally friendly cutting fluids. Numerous fluids, as well as a combination of new technologies that minimize the consumption of this resource or even eliminate it, are available to implement in different types of processes. The research effort is focused, first, on the study of biodegradable fluids; these friendly resources can substitute the conventional ones (mineral, synthetic and semisynthetic cutting fluids), some with limited availability and others which cause high environmental deterioration. The new fluids should meet certain characteristics (good lubricating properties, high cooling capacity, low viscosity, chemically stable, noncorrosive, high flash point, allergy free, less evaporative, and low cost) to maintain the machining performance that the conventional fluids offer [126]. Second, the research effort is focused on the development of new alternative technologies; the following are some of the more considered in the scientific and technical literature [75,127]: minimum quantity lubrication (MQL), near dry machining (NDM), compressed air cooling, cryogenic cooling, high pressure coolant (HPC), use of solid lubricants or coolants or nanofluids and nanoparticle in MQL. And finally, the most efficient way of employing fluids in the machining performance is studied, taking into account: (1) the minimization of the amount of fluid and (2) the search of the optimum MPP that maintain or increase the productivity (measured through tool life, cutting forces, surface roughness, power consumption or cost).

With regard to the optimization activities related to the cutting fluids, the studies are centered on two lines [128]: (1) toxicity reduction and (2) minimizing the amount used in the machining process. Ghosh and Rao [129] evaluated the sustainable machining methods available that use biodegradable and ecofriendly fluids (coolants and lubricants); these obtain good results in superficial quality, temperature, cutting speed, and tool use. Jayal et al. [130] studied how the options in cutting fluid usage, for MQL and NDM, affect the tool wear and the chip removal. With the aim of guaranteeing the processes efficiency, Weinert et al. [131] presented a detailed analysis of the dry machining options and MQL_ they analyze the adaptation of the cutting parameters, tools, and machine-tools for the different types of machining processes and for a variety of metallic materials. Finally, Klocke et al. [132] demonstrated that the use of *high-pressure lubricoolant supply technology* on metals that exhibit cutting difficulties offers the following benefits: (1) it reduces the general energy consumption, (2) it increases the productivity, and (3) it improves the process' stability by coordinating the setting parameters (supply pressure, flow rate, cutting parameters, tool design, tool wear, and chip forms).

To optimize the machining processes taking into account the type of fluids and its use of technology, the following variables are normally considered: lubrication method, depth of cut, number of revolutions, feed rate on the surface roughness.

Commencing with turning, Eker et al. [22] used the *Taguchi experimental design method*, *The signal-to-noise* (*S*/*N*)*, and the ANOVA* to determine the process' optimum levels; the authors analyze the influence in the cutting speed, feed rate, depth of cut, surface roughness, temperature, and cutting force for the two lubrication possibilities (dry and MQL). In milling, Jozic et al. [104] optimized operations that use compressed cold air cooling and dry machining, to maximize the volume of removed material and minimize surface roughness, flank wear, and cutting force components. And for grinding, [133], with the aim of reducing the amount of waste streams, Morgan et al. determined the optimum amount of lubricant needed.

3.4.3 Innovation and Cleaner Machining Processes. The proposal of new clean machining processes and the improvement of the existing aim to make available (to the industry) technologies that have the following objectives: (1) promote the conservation of raw materials, (2) reduce the energy consumption, (3) adequate management and minimize generated waste, (4) prevent and reduce contamination, and (5) protect the health and safety of people; this situation supposes new challenges for machine engineering [134]. The different drivers of innovation (Horizon 2020 [135]) that are proposed by the major international manufacturing investigation associations of the European Union (IMS2020 [136], Factories of the Future 2020 [137] or Industry 4.0 [138]) will achieve the goals through the design and development of clean technologies. These clean technological resources can guarantee the economic and technical feasibility of the conventional processes; in addition, they can include other benefits like sustainability, interoperability, and human-centered manufacturing.

For example, Alberdi et al. [139] created a *nozzle design for optimization* using CFD techniques for grinding; this equipment uses hybrid technology (hybrid MQL and *low-temperature* CO_2 cooling system) to improve the Performance Friction, superficial finish and tool life, and reduce fluid use. Nishikawa et al. [140] developed the *electric rust preventive machining method.* This element encourages the impact reduction in fluid use and CO_2 emissions. Salaam et al. [141] created the Ranque–Hilsch vortex tube, a device that does not have mobile parts that does not need electricity or chemical substances to achieve the minimum amount of lubrication. Finally, Goldberg [142] presented a set of innovative characteristics to include in the machining process' design; these increase productivity and profitability, and combined with the strategy MQL reduces the energy consumption and increases the environmental efficiency.

Furthermore, the hybrid processes are an opportunity to improve the production's environmental efficiency; these consist of two processes being carried out by the same machine tool. It is the case of Deiab [143] who analyzed the concept of sustainable hybrid machining (turn-grind and mill-grind) through the following variables: energy, lead time, CO_2 emissions, and preparation time; or Neugebauer et al. [144] who chose High Performance Cutting to minimize production time, cost and energy for turning, milling, drilling, grinding, and impact cutting.

In the proposals that refer to clean processes, the optimization of the selection of the process parameters (MPP) is converted into one of the most important areas of study; this is because the optimal MPP increases the efficiency and quality of the results. Xiong et al. [78] classified the main optimization methods of MPP in four categories: (1) test, (2) numerical simulation (with high time consuming and cost requirements, however with more realistic results), (3) expert/knowledge, and (4) algorithms. The category of expert/knowledge is focused on nonlinear problems with a virtual model; there is a variety of commercial software available for it. The problem is that, in general, they reduce the study to quality, not always being available or being difficult to include other parameters like cost, time, environmental or social efficiency. Algorithms can include different variables that are relevant to sustainability; however, making it very complicated to consider nonlinear parameters. The selection will depend on the level of development and implantation of the processes and the new technologies.

In this line, for example, Winter et al. [108,145] proposed a method to identify Pareto-optimal solutions (related to MPP for tool and cutting fluid) that increase the eco-efficiency in grinding; Lin et al. [146] developed a multi-objective teaching-learning-based optimization algorithm that selects the optimum MPP, aiming to reduce the carbon footprint and the machining time in turning.

3.5 Optimization of the Equity Dimension. The equity dimension [65] is in charge of studying the human well-being parting from a healthy environment and economic abundance that allows global and equitable development in all the populations and societies [64,65]. The general lines of study include activities that promote quality of life, shared knowledge, and social responsibility; the specific lines include the fundamental human rights and the cultural diversity, the basic needs right, education, a fair distribution of resources and healthy social areas; in the work context (organization level), the safety and health of workers, the training and education, equal opportunities, skill development, and job opportunities [96] are taken into account. This determines that equity is the strategic opportunity to integrate sustainability 3E, by educating society and raising their awareness and responsibility; this strategy will transform the goals of the economic dimension toward mitigating the metabolic rift [147].

In manufacturing, and in particular for machining systems (microlevel), the fields of action include the relationship between employee and company, security, worker health, and comfort tasks. It also includes studies of the functionality of the results, client relationship, and interferences with the stakeholders; among others, the design of the workstation and of the work environment should be addressed, taking into consideration the following aspects: (1) human factor (measured by the performance [148]), (2) the decrease of the physical and cognitive work load [149], (3) the productivity improvement [150], (4) the motivation [151], and (5) the training and information at the workstation [152].

The equity dimension has been the least considered in the machining engineering investigations; it was not until the last decade of the 20th century, when the interest in social aspects was included in the development of the paradigms for sustainable manufacturing [153,154]. This determines that the lines of research are in their initial development; the studies that plan to optimize social parameters are a minority compared with the other two dimensions. The most considered variables to study are *performance and human comfort, occupational health, and occupational risk prevention*.

In this section, the optimization and improvement process of the equity dimension in machining is analyzed taking into account four study aspects: Machine–human interaction, management and work teams, process automation and worker autonomy, and learning and skill improvement.

3.5.1 Human-Machine (H–M) Interaction. Although knowledge exists about the design and development of the machine tool and the interface human–machine (H–M) to improve the human performance and the employee protection, not many studies have been found which optimize the interaction human machine. In the literature, there are many studies that include improvements starting with the evaluation of the workstation. These improvements are based on the experience of the manufacturing engineer, researcher, or technician in occupational risk; the methods used, in their majority, follow an occupational risk evaluation norm. The H–M optimization lines are still in their early stages, where the effort is focused on the development of design models or methodologies; for this reason, there are not many optimization processes that improve the equity dimension in machining.

Between the two areas, study and evaluation, related with the worker's performance in the machining process, the studies analyze the following aspects: (1) the human ability (efficiency, precision, and errors) [150] and (2) the human performance (this is because with a better design of the task [155,156] or a better design of the machine tool [157] the productivity increases).

In the area of environmental ergonomics, the exposure of the employee to the different environmental factors is studied (such as noise [158], vibrations [159], cutting fluids [160] or emissions, toxic mist and air quality [161,162]). The consequences of performing the machining task, on the employee's health, are also evaluated [163,164].

In addition, several studies are carried out to adapt the dimensions of the machine to the worker, using the following areas of knowledge: static anthropometry [165], dynamic anthropometry [166], cognitive ergonomics [149], and cultural ergonomics [167], without forgetting, being able to adapt the workstation to a worker with special needs, for example, a disabled person [168].

In the optimization field, there are new lines of research that have been recently introduced in sustainable machining engineering; these are focused on improving the experience and comfort [149]. This is the case of Kansei engineering which considers the worker's psychological feelings in the design of the machine-tool, task, and environment [169]. This indicates progress in the design of machine tools, broadening the design parameters which, in general, only treat functional and ergonomic aspects from an anthropometric and biomechanical point of view. Highlighting here the contributions [170–172] that analyze the relationship between the worker and the machine-tool CNC with regard to the affections and emotions provoked by the interface; Wang et al. [173] provided a new focus based on the combination of Kansei engineering and "support vector machine scheme," to determine the design parameters related with semantics and the usability of the machine-tool; Lan et al. [35] used genetic algorithm combined with Kansei engineering to select the colors of the interface.

3.5.2 Management and Work Teams. The management of activities and operations in the production process and in the machining cells is an area of great importance; the productivity and efficiency of the shop floor, not only depends on the processes or the individual factors related to the workers but also on the interaction and effective coordination between the work groups. The creation of empowered teams is vital so that the employees (apart from possessing the required technical and administrative capabilities) cooperate in the following tasks: (1) identifying and resolving problems, (2) maintenance programing, (3) production activities, (4) material order, and also in (5) the process' continuous improvement by analyzing the tasks they carry out [174,175]. Even though there are not many studies, new forms of efficiency associated with *participatory approaches, collective decision making strategies, and occupational risk prevention* are included in the optimization of the work organization. In the machining field of planning, organization and process management, Seppälä [176] described machining cells with a participatory approach. They develop a way of organizing the work and new practices with collective decision making. Askin and Huang [174] propose the optimization model worker assignment and training (WAT); they use single-pass greedy heuristic for the formation of *efficient work teams with high synergy* who promote a cooperative working environment and individual job satisfaction.

3.5.3 Process Automation and Worker Autonomy. Interest in reducing the worker intervention and in automating the machining process has fomented the study of the optimization of intelligent machining processes. The aim is focused on minimizing human error when configuring the programs computer-aided manufacturing (CAM), and in an indirect way, increase the quality of the results and the autonomy of the machinist. This involves introducing artificial intelligence in the CNC environments; through metaheuristics (such as genetic algorithm), the most appropriate MPP and CAM program can be determined without having to depend on the human factor [32,33]. For example, Ramesh et al. [177] studied the advantages of *Rapid*-CAM. This system allows the intelligent automation of an auto configurable machine tool in real time (studying the inputs and outputs to make the decision concerning the tool or the MPP); Skamoto et al. [178] created a system based on Data Mining so that any worker can configure the process with sustainable behavior.

3.5.4 Learning and Skill Improvement. Simulation, virtual reality, augmented reality and e-learning (parting from machining laboratories and environments) are applied with more frequency in the worker training systems (learning and training session); they are used for different processes such as: CNC, programmable logic controller (PLC), supervisory control and data acquisition (SCADA), mechatronics and in embedded systems [179]. The simulators help to learn the task with training that is safe, more efficient and economic, being able to prolong it in time until the worker acquires the required capabilities and abilities; they also contribute in reducing work execution errors [152,180] while guaranteeing health and safety. There are numerous examples of virtual training environments; for example, the case of Wasfy et al. [181], who developed a simulator for three-axis CNC Milling; apart from offering a safe environment to work in, it provides the optimization option of the process plan by testing various plans on the virtual machine before real machining. To complement the training [182], some simulators include the evaluation of the workers experience and how this affects the machining results.

Also, and linked to the driver of innovation of Horizon 2020, new methodologies and strategies are introduced which improve the training in machining environments; these can integrate, for example, serious games (the use of games for nonentertainment purposes) and gamification (the use of game design elements in a nongame context). These learning strategies facilitate learning and increase motivation, apart from acquiring skills, experience, and productivity [183]. In this field, the project MecaGenius should be highlighted [184], a game developed for training in, mechanical manufacturing processes (including machining) with the aim of "*reinventing the manufacturing sector including green production.*" These learning and training systems contribute to the new expectations of Smart Factory, Virtual Factory, and Cloud Manufacturing (that include Internet of Things—IoT, virtualization and Distributed Computing Technologies [185]).

4 Results and Discussion: Characterization of Research Efforts

The interest in sustainable manufacturing is reflected in the review's results; these show the change that has occurred in the recent years, in the research lines related to the major paradigms (green manufacturing and cleaner production). In Table 3, the studies analyzed in the review are classified according to (1) the scope of the optimization process of sustainable machining and (2) the framework of 3E. On the whole, the studies do not cover the three sustainability dimensions, fulfilling some of the following three situations: (1) many of the optimization works only study one of the three sustainable dimensions, without taking into account the impact on the other two; (2) there is a growing trend where research covers two sustainable dimensions at a time; and (3) there are very few studies that address the three dimensions as a whole, working on the triple results of the 3E.

Figure 5 is the analytical synthesis of Table 3. It characterizes the research effort and organizes a set of the most relevant indicators of the last 10 years for the optimization of sustainable machining; it was calculated with the number of publications analyzed. This analysis verifies that the studies that focus on the 3E are few, and the equity dimension is included, however, only in the health and safety of the employee.

The economic dimension is placed as a comparative reference point, to study the technical and economic viability, when incorporating improvements in the other two dimensions. The environmental dimension (generally supported by the viability of the economic dimension) is the centerpiece of current research; energy and cutting fluids are the most studied lines. Little consideration has been given to the social perspective.

Analyzing the level and depth of development, the studies fulfill some of the following characteristics: (1) they are theoretically and qualitatively developed, trying to lay down the basis for integrating optimization and the continuous improvement in machining, orientated toward integral sustainability; they address strategies, principles or relevant axioms; or (2) they develop in depth a field, aspect or variable of optimization from one of the dimensions, testing its influence and finding its trade off for some selected parameters of the other two.

This situation is sustained because of how complex it is to include the trialectic relationship demands <humanity-production-nature> in a machining system. In many occasions, the complexity increases as a consequence of (1) the state of technology development, (2) resource availability, or (3) insufficient knowledge. In other cases, the set variables to optimize 3E are unknown. Furthermore, up till now, few proposals cover sustainability in an integral form; for this reason, the declared goal by many authors is the need of an integral index and methodology for the design, development, and sustainable optimization of manufacturing engineering, taking into account the three dimensions in a systematic form [193–195].

5 Proposal for Future Research in Optimization of Sustainable Machining Engineering

According to the results and discussion in Sec. 4, it is evident that the research effort is focused on the economic and environmental dimension. Additionally, it more thoroughly covers the parameters and indicators that can affect the process' performance and efficiency. Below, a profile of articulated investigation lines under the TBL is proposed; they are all needed so that machining engineering can assume the goal of finding a balance to achieve integral sustainability (Fig. 6). The lines have been classified according to the process' required inputs and outputs; each defines a set of adequate optimization variables to improve the significant characteristics of the machining process. This proposal includes directions and future lines of study that cover areas of knowledge, widely developed in manufacturing engineering. It also covers uncommon areas and unexplored topics within the optimization of sustainable machining; all of them are significant for sustainable manufacturing in the mitigation of the metabolic rift. Figure 6 divides the study of sustainable manufacturing in four areas: optimization of the machining process, machine tool, task, and worker situation. A set of possible optimization variables can be identified in them; these variables, selected in a multi-objective problem, will be able to reduce the process' metabolic rift. The focus of the optimization problems can have two scopes:

(1) Maximizing the machining process' sustainable value: improvements applied to the inputs (including the machine, the worker, the task and the process) and to the outputs, in particular, to the "reusable output streams."

Table 3 Classification of the studies reviewed

Main SD developed	General studies for machining optimization [16,17,19,20,37–42,78]		
3E	Refs. [57–63]		
EC	Refs. [24], [34], [36], and [67,75,77,81,82,84–88,91,92]	Refs. [25], [26], and [68,70,71,73,76,83, 89,90,93–95,98–102,105–107,187–191]	Refs. [74]
ENV	Refs. [22], [27], [76], and [96,104,108,114,117–119, 136,127,130–133,139,142–146]	Refs. [9] and [115,116,120–125, 128,129,140,141]	
EQY	Refs. [32], [33], and [152,174,177,180–182,186]	Refs. [178,183,184]	Refs. [35] and [170–173,191,192]
	EC(1)[a]	ENV(2)[b]	EQY(3)[c]

[a]EC(1): The paper includes a set of economic aspects to complete the aim topic.
[b]ENV(2): The paper includes a set of environmental aspects to complete the aim topic.
[c]EQY(3): The paper includes a set of equity aspects to complete the aim topic.

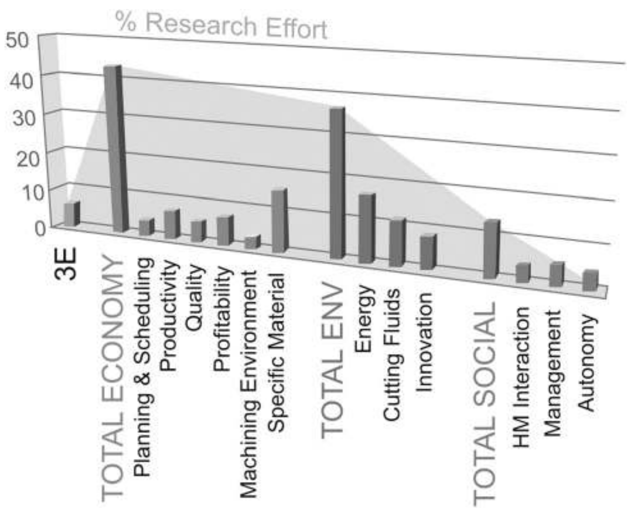

Fig. 5 Profile of research effort

(2) Minimizing the process' economic, environmental and social impact: control of the "nonreusable and waste streams."

To verify the improvements, the results will be evaluated in terms of process efficiency and through the environmental impacts generated and avoided; these should cover the three dimensions in a balanced manner:

- Ecological dimension: midpoint impact categories (for example, climate change, acidification, land use, etc.) and endpoint impact categories (damage to human health, damage to the quality of the ecosystem and damage to the resources).
- Equity dimension: categories related to the impact generated (1) at an individual level (for example, health and safety of the worker; or compliance to the client's expectations with products and services that are safe and of quality); (2) at a community level (reconciliation of the work and family life, equal opportunities, attention to the special needs population); and (3) at a social level (foment the population's health, equal opportunities, compensations for exploitations and change in land/territory use).
- Economic dimension: categories related with the increase in competitiveness, the local economic development, the financial yield or the commitment with the Research and Development activities.

The two approaches address the efficiency, consistency, and sufficiency strategies [196,197]; by carrying them out simultaneously, they will contribute to create economic, environmental, and social values in the sustainable machining process:

- **Efficiency Strategy** achieved in the machining process by controlling the consumption of resources and impacts. It contributes to reducing the consumption (raw material, energy, water, fluids, etc.) and to selecting the more adequate type of resources (raw material, technology, exchange between processes); all this will reduce the environmental and social impact as it minimizes the wastes and emissions generated.
- **Consistency Strategy** achieved in the machining process by the cyclicity (closed-loop system); it creates an "industrial symbiosis," closed cycles of products and by-products which form exchange networks. For this strategy, the outputs that are produced by each process should be identified, classified, and prepared for its next use (with control in real time); and the "symbiosis" should be created in the manufacturing systems (microlevel) and between manufacturing factories (macro level, for example, in eco-industrial parks). With this, the wastes are converted into "nutrients" or usable inputs

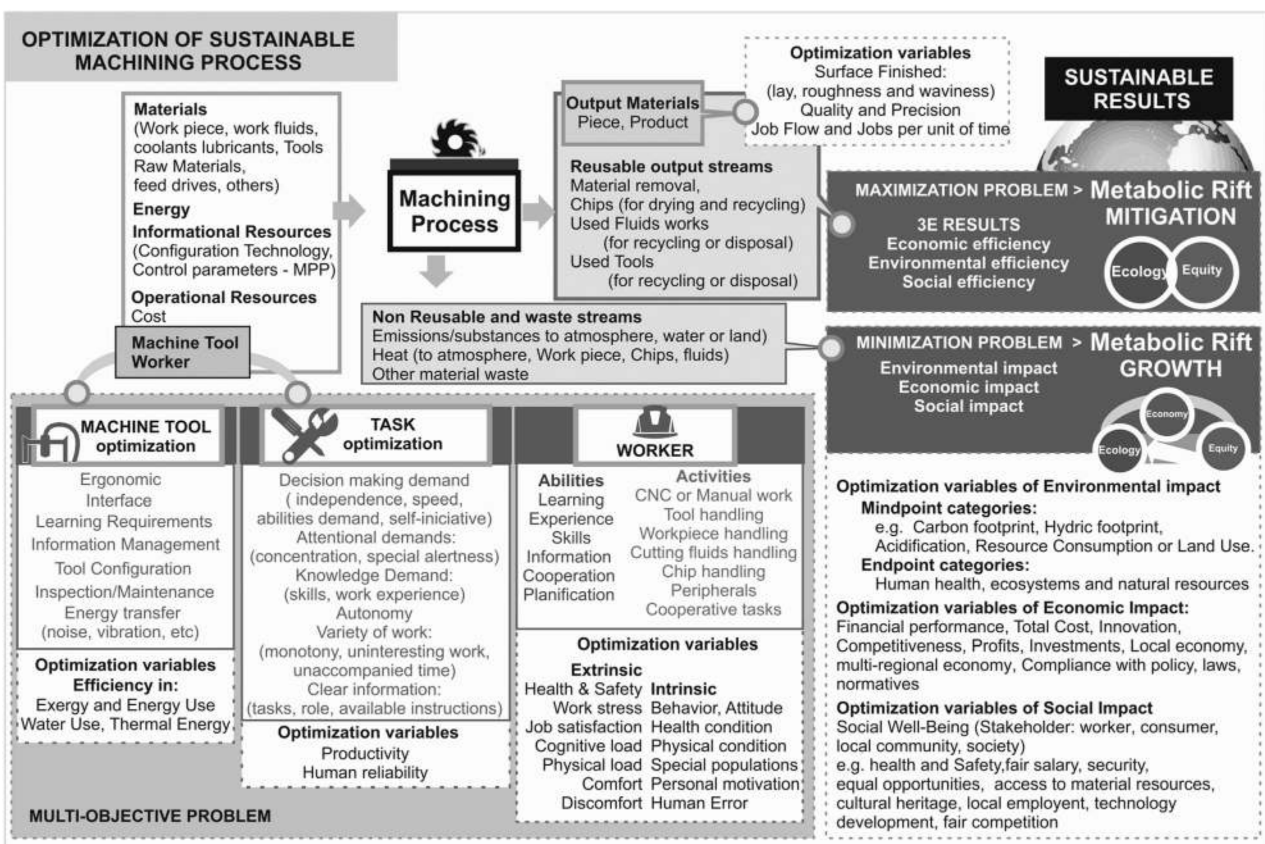

Fig. 6 Proposal of sustainable machining optimization

(waste = food) with maximum efficiency. It has to be taken into consideration that, for some outputs, a pretreatment, conditioning, and additional resources consumption, will be required (in order to be converted into by-products). For this reason, the cyclicity strategy should prioritize the waste and by-products management processes in the following order: (1) reuse, (2) remanufacture and reconditioning, (3) recycling, (4) energy valuation, and (5) final disposal.
- **Sufficiency Strategy** achieved in the machining process with the creation of value: it promotes eco-efficient machining processes (cradle to cradle). This situation implies that, apart from reaching zero-impact strategies, the processes will include plans to regenerate the damage caused previously (this is to say, it will contribute to the planet's recovery).

For this reason, "eco-innovation" and Corporate Social Responsibility strategies and recommendations should be followed:

- Material substitution: the use of degradable and recyclable materials. These materials require less effort in their end of life management. Being able to be reused by other processes: industrial, urban, rural, or even, natural (requiring the by-products' biodegradability).
- Promote the use of renewable energy.
- Dematerialization of the metabolic routes: reducing the material consumption. It can be achieved by applying broadened Lean strategies; this is to say, not only promoting the reduction of the "client's wastes or muda" but also the minimization of "nature's wastes."
- Economy restructuring toward circular economy: promoting new scale economies that make use of the generated by-products.
- Extending the process' economic considerations: including the "environmental cost" or the "social marginal cost," just like the "social marginal benefits" or the "environmental marginal benefit" in the economic cycle.

6 Conclusions

In this review paper, the research effort is analyzed and driven for engineering machining to optimize the sustainable machining process. This study has identified the current situation of the investigation regarding sustainable machining and the trends for future lines of research; furthermore, the study areas proposed can be used to reach and develop the new challenges for the Horizon 2020 programs of the European Union. The new challenge for sustainable machining is the structuring, the simplification and the complexity reduction with regard to integral sustainability using the framework triple bottom line; this strategy could be an opportunity for continuous improvement to orientate manufacturing toward excellence. This means that sustainability, as a competitive core idea, should be considered for the optimization of the machining processes, where material efficiency, low energy consumption, and cyclical metabolism can contribute to the mitigation of the metabolic rift and simultaneously to the creation of quality of life.

Nomenclature

CAM = computer-aided manufacturing
CNC = computer numerical control
CP = cleaner production
EC = economic dimension
ENV = environment dimension
EQY = equity dimension
GM = green manufacturing
HPC = high pressure coolant
MPP = machining process parameters
MQL = minimum quantity of lubricant
NDM = near dry machining
OP = optimization process
PLC = programmable logic controller
SCADA = supervisory control and data acquisition
SM = sustainable manufacturing
SME = sustainable manufacturing engineering
TBL or 3E = triple bottom line
WAT = worker assignment and training

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