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Energy-Based Novel Quantifiable Sustainability Value Assessment Method for Machining Processes

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Abstract: Sustainability assessments of cooling/lubrication-assisted advanced machining processes has been demanded by environment control agencies because it is an effective management tool for improving process sustainability. To achieve an effective and efficient sustainability evolution of machining processes, there is a need to develop a new method that can incorporate qualitative indicators to create a quantifiable value. In the present research work, a novel quantifiable sustainability value assessment method was proposed to provide performance quantification of the existing sustainability assessment methods. The proposed method consists of three steps: establishing sustainable guidelines and identifying new indicators, data acquisition, and developing an algorithm, which creates the Overall Performance Assessment Indicator (OPAI) from the sustainability assessment method. In the proposed algorithm, initially, both quantitative and qualitative sustainability indicators are normalized. After weight assignment and aggregation, the OPAI is obtained. The developed algorithm was validated from three literature case studies, and optimal cutting parameters were obtained. The present methodology provides effective guidelines for a machinist to enhance process performance and achieve process optimization. The study also offers a relationship between sustainable and machining metrics for the support of industrial sustainability.

Keywords: sustainability; Overall Process Assessment Indicator (OPAI); sustainable machining; energy consumption; environmental impact; machining costs; waste management

1. Introduction

The development of sustainable manufacturing processes is becoming inevitable for the manufacturing industry. Sustainability does not solely address environmental issues; it also concerns social equity and economic development.

Production time, electrical power and energy consumption, production cost, carbon emissions, waste management, personal health and safety, and water consumption are the major sustainable metrics [1]. The machinability factors include surface quality, cutting force, cutting temperature, residual stresses, and chip characteristics. Each sustainability factor further consists of sustainability indicators. Sustainability indicators (SIs) are the quantitative or qualitative measures of the sustainability performance of products or manufacturing processes in terms of sustainability aspects. The SIs are classified into two categories, i.e., quantitative indicators and qualitative indicators. The quantitative indicators include CO_2 emission, electrical power and energy consumption, and production cost [2]. These indicators can be measured physically using instruments or calculated by using equations. However, qualitative indicators are assessed via expert opinion, International Organization for Standardization (ISO) standards, and surveys. It includes personnel health risks, safety, and customer satisfaction.

The sustainable value creation of products and services has become essential. Sustainable values consist of economic, environmental, and societal values. Economic values are relatively easy to calculate. However, environmental and societal values are difficult to obtain from the perspective of manufacturing processes. It is very difficult to define and establish a methodology for the value assessment of societal and other qualitative indicators. Mechanical machining is a widely used operation in the manufacturing industry. Thus, developing a sustainable value framework for advanced lubrication/cooling (lubricooling)-assisted machining processes will be a very effective tool for a machinist.

Initially, it is necessary to understand the existing methods of sustainability assessment since there is a dire need to develop sustainable guidelines based on the triple-bottom approach (TBC), 6R, life-cycle assessment (LCA), and energy, environment, economy (3E) methods. Therefore, it is an essential task to quantify sustainable value generation, which requires the quantification of environmental and societal metrics. The sustainable metrics were selected from the guidelines to develop a sustainability performance evaluation methodology. The proposed methodology defines sustainability metrics based on sustainable guidelines to evaluate the Overall Performance Assessment Indicator (OPAI) at the process level.

2. Literature Review

During the manufacturing processes, machine tools, workers, and equipment come together to add value to the material and produce mechanical parts. Machining is a key process in the manufacturing domain. The performance of machining processes from the machinability perspective has been studied by many scholars [3,4]. It is very difficult to machine hard materials, such as Haynes and titanium- and nickel-based alloys. These alloys are used in the aerospace and military industries. In the past, authors have proposed various technological measures to improve the machinability of difficult-to-cut materials [5].

Jawahir and Jayal [6] proposed a new methodology for the assessment of sustainability dimensions of the machining process. The authors used empirical and analytical techniques to develop their algorithm to predict the sustainability elements of machined products. Badurdeen et al. [7] introduced a new approach for sustainable supply chain management (SCM) based on the total life cycle of a product. Unlike conventional practices, the new approach also included recovery, redesign, and remanufacture stages. Joshi et al. [8] proposed a new closed-loop 6R methodology for sustainable manufacturing. The 6R approach added three more new stages to the recovery, redesign, and remanufacture stages in the traditional approach. Jawahir et al. [9] worked on the 6R methodology for sustainability assessments in manufacturing processes. However, the authors did not quantify the qualitative indicators. Feng et al. [10] defined the sustainability-related guidelines of a product for its entire life cycle. The authors considered the stock material preparation, manufacturing, distribution, customer use, and post-use stages to investigate three universal aspects of the TBC. General guidelines for sustainable products were already available in the literature. However, Fiksel et al. [11] gathered holistic data from various companies and established quantification values through a sustainability performance measurement framework. The framework was based on three aspects, i.e., the triple-bottom approach, resource consumption, and the full life cycle.

Pusavec and Kopac [12] highlighted the main sustainability indicators, i.e., waste management, environmental issues, electrical energy consumption, machining costs, and personal health and operational safety. In addition, the authors calculated the production cost of dry and cryogenic-assisted machining processes. Reich-Weiser et al. [13] mainly focused on the sustainability assessment of a material processing industry (GM Motors). The authors established a top-down approach that highlighted the sustainability metrics, including environmental-cost- and energy-consumption-related metrics. In the past, several sustainability performance rating systems have been designed. For example, the Global Report Initiative (GRI) consists of 70 indicators, and the Ford Product Sustainability Index was proposed based on 8 indicators [14].

Khan et al. [2] conducted external turning experiments as part of holistic investigations of the nanofluid-assisted machining process. In the experimental study, the authors developed novel empirical models based on the energy, environment, economy (3E) approach. In another study, Priarone et al. [15] used the 3E approach to find optimal cutting parameters for the conventional emulsion-assisted machining process. Optimal cutting parameters were found for electrical energy demand, production time, cost, and carbon emissions. However, the authors did not address waste management and personal health and safety. Khanna et al. [16] conducted cryogenic–ultrasonic-assisted turning (CUAT) and cryogenic-assisted turning (CAT) experiments for the machining of Nimonic-90 alloys and investigated the sustainability and machinability aspects. Results revealed that 20% less energy consumption and CO_2 was emitted from CUAT as compared to CAT. In another study, Khanna et al. [17] reduced power consumption from the ultrasonic-assisted turning of Nimonic-90 alloys. The authors used a hybrid particle swarm with simplex methods (PSO–SM), where it was found that the proposed machining method can reduce the electrical power consumption by 8–10% when compared with ordinary turning. Agrawal et al. [18] developed a new cryogenic–ultrasonic minimum quantity lubrication-assisted machining setup and used traditional methodology for the analysis of sustainability and machinability aspects. The results showed that the proposed hybrid cooling approach improved sustainability during Ti-6Al-4V turning.

A state-of-the-art review paper on the holistic energy consumption of machine tools was published by Khan et al. [19]. The review paper reported on various aspects of energy reduction strategies. Mia et al. [20] considered cutting energy, surface quality, and productivity as response parameters. In addition, the authors used an LCA of cryogenic liquid nitrogen (LN_2)-assisted machining. Numerous efforts are also made for the reduction of CO_2 emissions from the machining process. Sing et al. [21] compared the electrical energy consumption and carbon emissions between Ranque–Hilsch vortex tube (RHVT) and conventional Minimum Quantity Lubrication MQL-assisted machining processes. The results showed that RHVT has the potential to reduce carbon emissions by 45 to 56% in contrast with conventional MQL. The economic pillar of the TBC approach was also studied by many researchers. In a recent study, Khan et al. [22] investigated the production of dry machining and mono and hybrid nanofluid-assisted machining processes. Their results showed that the hybrid nanofluid-assisted machining processes produced 4.7% less CO_2 compared to conventional machining methods.

The abovementioned literature reviews mainly focused on either machinability- or sustainability-based investigations of machining processes. Most of the studies were published on conventional, dry, or emulsion-assisted machining. Finding a set of optimal cutting parameters for advanced lubricooling-assisted machining processes has become inevitable. There is a dire need to include sustainability indicators that consider resource consumption as well. For example, energy consumption and carbon emissions from nanofluid and liquid nitrogen have not been addressed before.

Researchers have investigated the sustainability assessment of many manufacturing processes. However, integrating the machinability and sustainability aspects to generate a quantifiable sustainability value is very necessary for understanding the process performance. According to the authors' best knowledge, sustainable value creation for the advanced lubricooling-assisted machining processes has not been addressed in the past. This research work covered (1) establishing sustainable guidelines for sustainable (dry, nanofluid- and cryogenic-assisted) machining processes, (2) developing an energy-integrated heuristic algorithm for sustainable machining, (3) quantifying environmental and societal indicators to generate a quantifiable sustainability value, and (4) model validation through three case studies.

3. Measuring the Sustainability Value of a Machining Process

The word sustainability can be defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Various methods have been adopted to evaluate the sustainability of the machining process. Each study contains a different set of metrics to evaluate sustainability, which makes this process complex.

A synergistic and holistic analysis is usually performed for the evaluation of the sustainability of a machining process. Sometimes, the life cycle assessment of production has been used as a sustainability assessment of the machining process. Several elements can be studied for the sustainability assessment, which are shown in Figure 1.

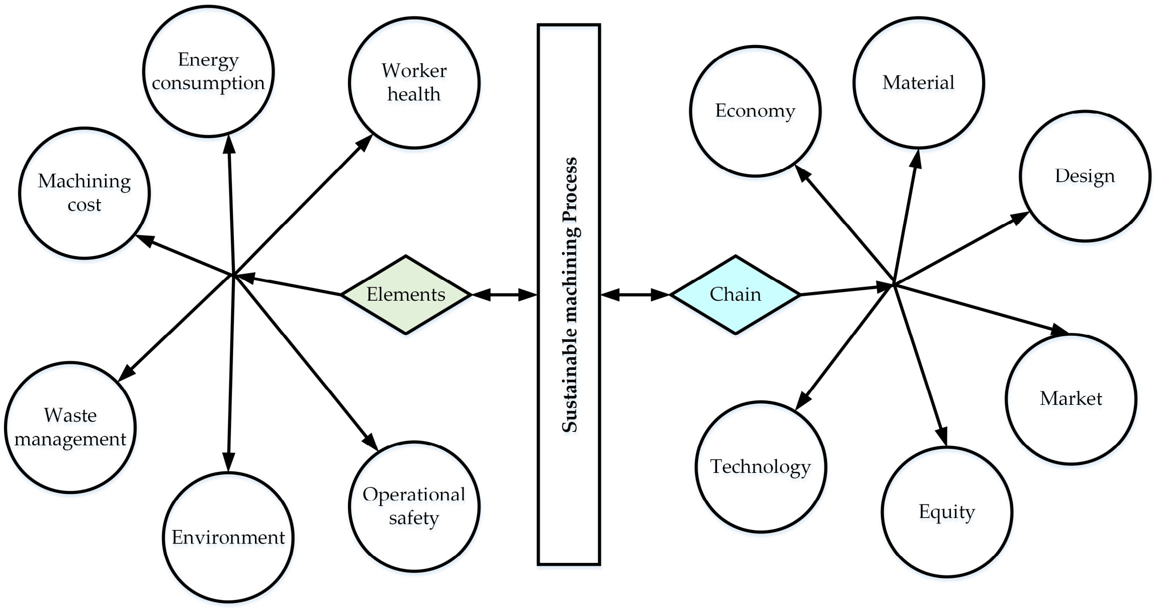

Figure 1. Fundamental elements of a sustainable machining process and the chain of product sustainability [6].

In the past, researchers studied the machining process from a sustainability point of view and made sure the process should have a lower environmental burden, be eco-benign, be harmless to worker health, and most importantly, it must be economical. The sustainability of the process also mainly depends upon the system boundary selected. If the system boundary is small, only a few indicators can be selected for the process evaluation [23]. For a holistic analysis, four stages are commonly considered, namely, acquisition of raw material, manufacturing, use/reuse, and recycle and waste management.

The National Council for Advanced Manufacturing (NACFAM) accentuated the "sustainable" products and "sustainable manufacturing" in the metal processing industry [24]. In another study, it was stressed that sustainable manufacturing must improve not only the resource and machine tool energy but also reduce environmental impacts. Furthermore, it must offer greater safety and produce minimal waste without compromising the quality of the workpiece [6]. In the past, researchers used the three following major concepts repeatedly to evaluate the sustainability of the specific process.

3.1. 6R Approach

The six stages named reduce, reuse, recycle, recover, redesign, and remanufacture are often called the 6R approach. The stages demonstrate the material flow through the system boundary. The 6R approach starts with reduce, which emphasizes the reduction of resource consumption. For example, recently, advanced manufacturing technologies have been proposed that can reduce resource consumption without compromising process efficiency. This approach also emphasizes the reuse and recycling of products, which can reduce the severe impacts of energy-intensive processes on the environment. Redesigning the already built technology is essential for improving the performance of the process. During the redesign stage, the environmental burden of the products and the process are considered. Similarly, natural resources, energy, and costs can be saved by remanufacturing the products. Hence, the 6R approach is an effective way to analyze the sustainability of the process. However, it is necessary to quantify the sustainable values of the 6R approach. The concept of the 6R approach is shown in Figure 2.

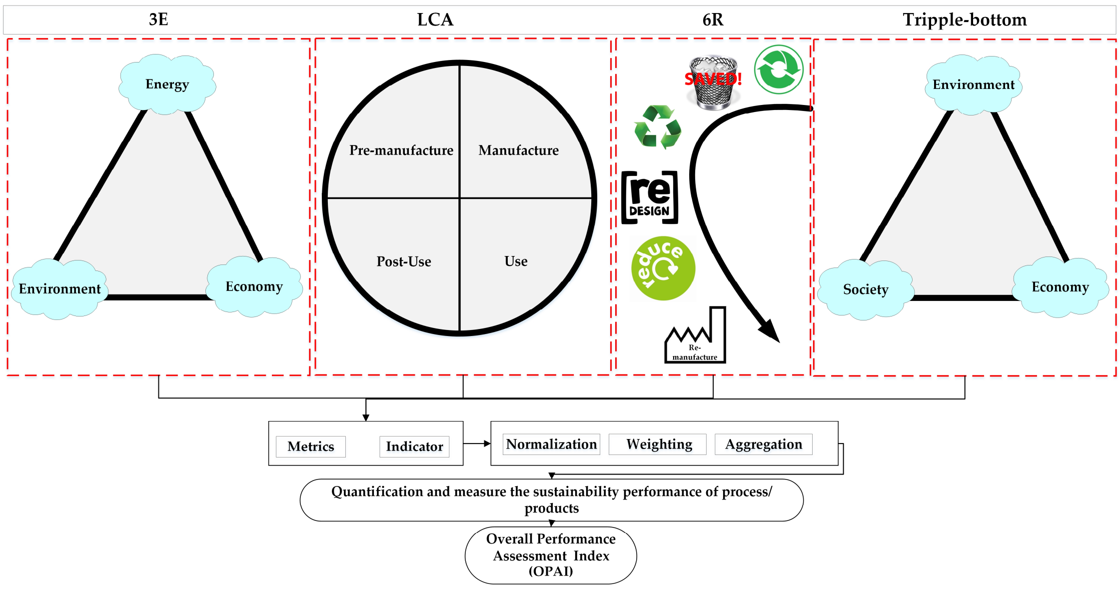

Figure 2. Methodology for the quantification of sustainability values of the process.

3.2. Triple-Bottom Approach

In conventional practice, only the manufacturing cost is evaluated, and based on this cost estimation, the environmental and societal impacts are assessed. However, a TBC works in a holistic system and considers the economic, environmental, and societal aspects as three fundamental pillars of sustainability. A separate sustainable value for each metric can be achieved for the environmental and economic impacts of a specific process.

The manufacturing process needs renewable and non-renewable resources to produce industrial products for the welfare of society. The triple bottom line makes sure that the resource consumption is low to reduce the process's impact on society and the environment. In the past, researchers evaluated the triple-bottom approach as a qualitative tool analysis [7]. However, it is necessary to develop a state-of-the-art heuristic algorithm that can quantify sustainability values. The triple-bottom approach is displayed in Figure 2.

3.3. Life-Cycle Assessment

Cradle-to-grave analysis of discrete part production is often performed by considering the total life-cycle assessment, which includes four stages: pre-manufacturing, manufacturing, use, and post-use, as highlighted in Figure 2. In an LCA, each phase deals with various processes and it needs to incorporate various stakeholders. Thus, the sustainability assessment of each phase depends upon its factors and the average impact of all phases is taken into consideration to evaluate the process. The various environmental effects of products and services are quantified and compared, the obtained results are used to make the best decision and improve the process [25].

3.4. 3E-Based Assessment

3E-based analysis is another method that is used to evaluate the sustainability of a machining process. The three Es stand for energy, environment, and economy [2]. These three approaches are different from LCA as it replaces society with high concern for energy consumption. Researchers have employed the 3E-based sustainability method in processes such as gas generation systems [26]. However, the same concept can also be used to evaluate the sustainability of a machining process. However, an assessment of the machining process alone is not enough to achieve sustainability targets. Thus, in this paper, sustainable guidelines are proposed for the 3E assessment method by including the engineering means for the evaluation of the used technology. After introducing all the guidelines from the sustainability indicators, a novel OPAI was proposed.

4. Guidelines for Sustainable Machining

A few years ago, Badurdeen et al. [27] studied the major metrics and indicators involved in the manufacturing process and proposed a guideline for sustainable manufacturing. The authors studied some of the indicators under major metrics. The same concept was used for our specific machining process to develop an extended guideline for the process. Production time, electrical power, energy consumption, cost, waste management, worker health, and the safety and environmental impacts were considered as the metrics for the manufacturing process. The guidelines for each metric are provided in the following sections.

4.1. Production Time

Production time is an important parameter that directly influences both electrical energy and resource consumption. Machining time during the turning process consists of the idle time and the setup time. It is worth mentioning that the setup time is the sum of the workpiece, cutting tool setup time, and handling time. The air cutting time is the time when the tool moves but does not cut the workpiece. Similarly, the cutting, tool change, and cooling and lubrication time are also part of the total machining time [28]. It is essential to highlight the indicators in the production time metrics. For example, the standby time is the sum of the setup time and the idle time. The setup time includes two stages, the cutting tool change stage and the workpiece handling stage. During the cutting time, the workpiece and cutting tool interact with each other, and material is removed by the cutting mechanism. Furthermore, other time factors, such as the transportation time, storage time, and cleaning and disposal time, also affect the overall sustainability of processes.

4.2. Power and Energy Consumption

The power demands from the different components of machine tools vary and it is tough to determine each component's demand. The power structures in the machining process change with the functionality states of the machine tools. However, in general, maximum power is consumed when all components of the machine tool are active. These components consume power in the functional stages of a machine tool. These stages are idle, set up, air cutting, cutting, tool change, and lubrication and cooling. Energy consumption is the second important metric considered under the guidelines of a sustainable machining process. Sustainability indicators related to energy consumption are considered in the guidelines and are shown in Table 1. The measurements of sustainability indicators under the domain of energy consumption are described in detail in [22].

Table 1. Types of electrical and embodied energy consumptions and their indicators.

Sustainability Factor	Sustainability Indicator		Definition and Measurement Method
Energy consumption, E	Electrical energy consumption	E_{sb}	Energy consumption during the standby stage (kWh)
		E_a	Energy consumption during the air cutting stage, (kWh)
		E_c	Energy consumption during the cutting stage, (kWh)
		E_{tc}	Energy consumption during the tool change stage, (kWh)
		E_{col}	Energy consumption during the coolant impingement, (kWh)
		E_{lub}	Energy consumption during the lubricant impingement, (kWh)
		E_{CT}	Embodied energy of the cutting tool, (kWh)
		E_{mf}	Electricity consumption to maintain the facility environment, (kWh)
		E_t	Transportation electricity consumption (kJ)
	Embodied energy consumption	E_{Wp}	Energy used to produce a unit volume of material, (kJ)
		E_{oil}	Embodied energy of the lubricant oil, (kJ)
		E_{emuls}	Embodied energy of the emulsion, (kJ)
		E_{LN2}	Embodied energy of the liquid nitrogen, (kJ)
		E_{cl}	Embodied energy of the cleaning stage, (kJ)
		E_{cc}	Energy used for the chip collection, (kJ)
		E_{cfr}	Energy required to recycle or recover the cutting fluid, (kJ)
		E_m	Energy required to produce the cutting fluid, (kJ)
		E_d	Energy required to dispose of all kinds of parts and resources, (kJ)

4.3. Cost

One of the most important parameters for a performance evaluation is an economic comparison. The cost model presented in Kalpakjian et al. [29] showed major limitations. It described the production cost defined as the sum of the (1) machining cost, (2) tool change cost, and (3) cutting tool cost. However, costs due to non-cutting stages, particularly the lubrication stage and the advanced lubricooling process (MQL and cryogenic) were not addressed in detail. Hence, new cost models were developed to estimate the cost per part of sustainable and non-sustainable techniques. It is important to mention that the energy cost, machining cost, cutting tool cost, LN_2 cost, MQL oil cost, emulsion cost, cleaning and disposal cost, and environmental cost should be considered.

In the present study, a lot of indicators were included for the cost metrics (Table 2). The general guidelines about costs demonstrate the details about all indicators of the cost measurement. Dry, MQL, Nanofluid MQL NFMQL, cryogenic, and hybrid CryoMQL assisted machining processes are the best examples of sustainable machining. Most of the indicators in all kinds of lubricooling-assisted machining processes are the same, such as the cutting tool cost, workpiece cost, and coolant cost. However, some cost components are specific for specific processes. For example, the cost of nanoparticles and the cost of nanofluid preparation is only used for NFMQL-assisted machining processes. Thus, guidelines for sustainable machining processes are given herein. The measurements of the sustainability indicators under the domain of energy consumption are described in detail in [2].

Table 2. Direct and indirect costs and their indicators.

Sustainability Factor	Sustainability Indicator	Definition and Measurement Method
Cost	C_e	Energy cost
	C_m	Machining cost
	C_{CT}	Cost of the cutting tool
	C_{LN_2}	Cost of the liquid nitrogen
	$C_{emulsion}$	Cost of the emulsion
	C_{oil}	Cost of the base oil
	C_{np}	Cost of the nanoparticles
	C_{env}	Environmental cost
	C_{Wp}	Workpiece material cost
	C_{oil}	Cost of the base oil
	$C_{emulsion}$	Emulsion cost
	C_{LN2}	Cost of the liquid nitrogen
	C_{cl}	Cost of the cleaning stage
	C_d	Cost of the disposal
	C_{cc}	Cost of the chip collection
	C_{cfr}	Cost required to recycle or recover the cutting fluid
	C_{cfp}	Cost required to produce the cutting fluid
	C_{dr}	Cost required to dispose of all kinds of parts and resources
	C_{pg}	Packaging-related cost
	C_{tn}	Training cost
	C_{mt}	Maintenance cost
	C_{jf}	Cost of jigs/fixtures investment

4.4. Waste Management

Waste management is a very important process in industrial workshops, and ISO has imposed some standards to keep the workshop clean. Badurdeen et al. [27] discussed several indicators that are used to assess the sustainable value of waste management. However, some additional indicators were also considered in this study.

- Remanufactured scrap, WM_{rms}

The WM_{rms} can be calculated from the ratio of the total mass of the remanufactured scrap (m_{rms}) and total mass of the scrap (m_s). It can be defined as in Equation (1):

$$WM_{rms} = \frac{m_{rms}}{m_s}. \tag{1}$$

- Recycle chips, WM_{rc}

Recycle chips are quantified as the ratio of the total mass of recycled chips (m_{rc}) to the mass of the total chips (m_{chip}). It can be expressed as follows:

$$WM_{rc} = \frac{m_{rc}}{m_{chip}}. \tag{2}$$

- Disposed chips, WM_{dc}

During the recycling process, not all chips can be recycled, where some of those that do not qualify for recycling must be disposed of properly. Chip disposal can also be quantified as the ratio of total disposed chips (m_{dc}) to the total mass of the chips:

$$WM_{dc} = \frac{m_{dc}}{m_{chip}}. \tag{3}$$

- Recycle scrap, WM_{rcs}

Cutting tools are a major part of recycled scraps. Tool holders and fixtures also face wear and tear, but they have relatively long lives. Thus, recycled scrap can be defined as the ratio of the total mass of all kinds of recycled scrap to the total mass of scrap:

$$WM_{rcs} = \frac{m_{rcs}}{m_{scrap}}. \tag{4}$$

- Disposed scrap, WM_{ds}

It is also a fact that not all scrap can be recycled or remanufactured. Scrap with extremely bad quality is separated and must be disposed of. The sustainable value of disposed scrap can be defined as the ratio of the total disposed scrap to the total mass of scrap, as shown in Equation (5):

$$WM_{ds} = \frac{m_{ds}}{m_{scrap}}. \tag{5}$$

- Mass of mist generation, WM_{mg}

During the MQL spray, a mist is generated, and quantification of the mist generation is necessary. It can be quantified as the ratio of the mist generated to the total mass of the spray, as follows:

$$WM_{mg} = \frac{m_{mg}}{t_m}. \tag{6}$$

- Recycle/recovered metalworking fluids, WM_{RMWF}

Unlike MQL, during a flood-assisted machining process, cutting fluid is not used one time and it can be recycled after its life. It can be expressed as the ratio of the recycled metalworking to the total mass of the metalworking fluid, as follows:

$$WM_{RMWF} = \frac{m_{RMWF}}{m_{MWF}}. \tag{7}$$

- Disposal of metalworking fluids, WM_{DMWF}

The disposal of MWFs is inevitable after their application in a workshop. The disposal of cutting fluids can be defined as the ratio of the disposed of cutting fluid to the total cutting fluid used:

$$WM_{DMWF} = \frac{m_{DMWF}}{m_{MWF}}. \tag{8}$$

- Idle electricity consumption, WM_{ie}

During the break time of the maintenance of a machine tool, unnecessary electrical appliances must be switched off to reduce electricity consumption. Work idle time during the shift time is also a major factor for idle electricity consumption. It can be demonstrated as the ratio of the idle electricity used to the total electricity used:

$$WM_{ie} = \frac{E_i}{E_t}. \tag{9}$$

4.5. Personal Health and Operational Safety

It is also necessary to define guidelines for the personal health and safety of workers. Very little literature is published on the guidelines for worker health and safety for advanced machining processes. In this work, six indicators for worker health and safety were included.

- Noise level of the working environment P_{nl}

The noise levels in a workshop significantly affect workers' health. The indicator of the noise level can be classified into two parts. A noise level up to 90 dB is assigned 1 and a noise level of more than 90 dB is assigned value 2. The quantification of the noise level helps to reduce noise pollution.

- Environmental conditions P_{ec}

The environmental conditions indicator P_{ec} defines the working atmospheric conditions of workshops in metal processing industries. A sustainable value of P_{ec} can also be assigned a 1 or a 2. The values 1 or 2 are assigned according to the wet-bulb globe temperature. If the measured value of the temperature is up to 28 °C (82 F), it is assigned a value of 1, and a value of 2 is assigned for higher values. It is pertinent to mention that these values do not require previous criteria and are selected manually.

- Personal health index P_{hi}

The illumination level of the working environment is expressed in the personal health index P_{hi}. If the illumination level is less than 807 lux (75 fc), it is given a value of 1, and if it is more than 807 lux (75 fc), then a value of 2 is assigned.

- Total injuries rate P_{tir}

The total injuries rate is an alarming indicator under the personal health and operational safety metric. Several injuries per shift or per project are counted and its sustainable values are assigned according to the protection time according to ISO rules and regulations.

- Exposure to corrosive substances OS_c

This includes dust, mists, and the application of toxic chemicals. The exposure to corrosive substances can be explained as the exposure of all kinds of corrosive substances that are toxic to workers and the environment. It can be measured in incidents per person per processing time. Emissions that cause negative effects are scored as either 1, 2, or 3, which depends upon the type of fluid used and the percentage concentration of nanoparticles used.

- Exposure to a high-temperature surface OS_{hts}

During the machining of difficult-to-cut materials, the machinist has to face high-temperature surfaces. The sustainable values of this indicator are assigned according to the value of the temperature. Mostly, temperature values are categorized into two levels, where level 1 represents the temperature values less than 600 °C and temperature values that are more than 600 °C lie within the second category.

- Exposure to high-energy components OS_{hec}

The machine tool uses its maximum energy consumption during the machining process. In academia, mostly lower power rating machine tools are used. However, machine tools with total power up to 200 kW can be found in the industry. In this scenario, some components are energy-intensive and the worker may get injured while power measurements. It can be quantified as the injuries per person.

- Exposure to high-speed components/surfaces OS_{hss}

Exposure to high-speed components/surfaces is an independent indicator. The sustainable value of this indicator can be assigned as either 1 or 2, where it mainly depends upon the range of the cutting speed. For example, a cutting speed less than 900 rpm is assigned a value of 1 and a cutting speed of more than 900 rpm is assigned a value of 2.

4.6. Environmental Impacts

Environmental impacts are mostly characterized in terms of the CO_2 emissions during the cutting process. These CO_2 emissions are due to different components and/or different stages. The carbon emissions signature of the Nanjing power grid was used to find the sustainable values of the indicators. Some additional guidelines are as follows.

Direct and indirect activities that use energy also contribute to carbon emissions. As such, during the machining process, each process stage contributes to carbon emissions depending upon the corresponding process time. The total carbon emissions for the machining process is the sum of the carbon emissions due to computer numerical control (CNC)-machine-related activities and carbon emissions due to ancillary components. In this model, the carbon emissions for cleaning and disposal activities are also considered. The carbon emissions during each stage are calculated.

- Carbon emissions in the machining process

CO_2 emissions due to the electrical energy consumption of a machine tool mimic the trends of the cutting energy. Carbon emissions are negative outcomes of power generation because power generation requires coal, oil, gas, and biomass [30]. The electrical energy produced by different types of fuels and its information is given in Table 3.

Table 3. The energy produced by various types of fuels.

No.	Type of Fuel	1 GJ of Heat Produced	Release ΔH (kJ)	Release CO_2
1	Biomass	$CH_2O + O_2 \rightarrow CO_2 + H_2O$	−440	100 kg
2	Heavy oil	$C_{20}H_{42} + 30O_2 \rightarrow 20CO_2 + 21H_2O$	−13300	66 kg
3	Coal	$C + O_2 \rightarrow CO_2$	−394	112 kg
4	Natural gas	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	−440	49 kg
		ΔH = Enthalpy		

The complete combustion of coal emits a huge amount of CO_2. For example, the combustion of 1 ton of coal generates 2.86 tons of CO_2. Various types of fuels used to produce electricity are depicted in Figure 3. Three power grids of different countries and their input fuel types are tabulated in Table 4.

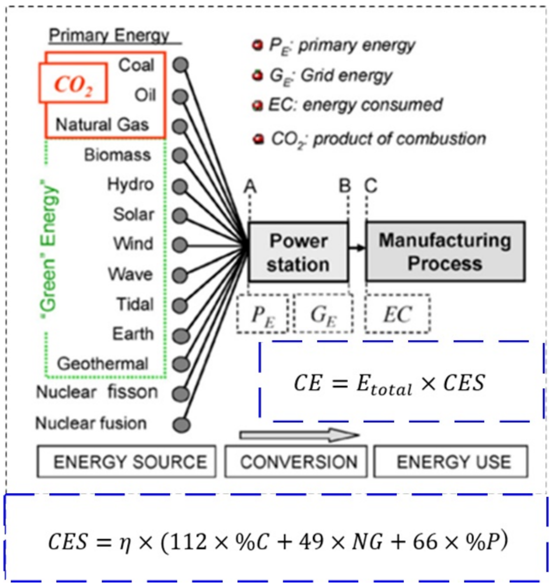

Figure 3. Primary energy supplies available [31].

Table 4. Three power grids of different countries and their input fuel type.

Fuel Supply	Ontario (%)	NSW (%)	Nanjing
Coal (C)	19	83.9	73.09
Natural Gas (NG)	7	8.5	12.1
Petroleum (P)	0	0.3	0
Biomass (B)			
Solar (S)	23	7.3	6.92
Hydropower (H)			0.09
Wind (W)			5.96
Geothermal (G)			
Earth (E)			
Wave (Wa)			
Tidal (T)			
Nuclear (N)	51		1.8
Total	100	100	100

The total carbon emitted in the process can be obtained by total energy consumption multiplying by carbon emission signature (*CES*).

$$CE = E_{total} \times CES \tag{10}$$

where *CE* is the amount of total Carbon Emission and E_{total} is a total electrical energy consumption.

Usually, a local power grid has multiple primary energy sources and their abbreviations have been listed in Table 4. Every power grid has a specific *CES*, which mainly depends upon the input source used to produce the electricity. Before the assessment of the carbon emissions in the machining stages, it is essential to determine the carbon emission signature:

$$CES = \eta \times (112 \times \%C + 49 \times NG + 66 \times \%P). \tag{11}$$

The carbon emissions per part due to the machining stages can be calculated as follows:

$$CE_m = E_m(\mathrm{J}) \times CES\left(\frac{\mathrm{kgCO_2}}{\mathrm{J}}\right), \tag{12}$$

E_m and CE_m are electrical energy and its footprints for part production, respectively.

- Carbon emissions due to the cutting tool

As discussed earlier, the fabrication of cutting tools is an intensive process and environmental impacts of the fabrication of cutting tools can be obtained from the literature. The carbon emitted per part due to fabricating a cutting tool can be explained as:

$$CE_{CT} = \frac{CF_{CT}}{T_L} \times t_c, \tag{13}$$

where CF_{CT} is the carbon factor of the cutting tool and T_L is life of cutting tool. Carbon emissions due to LN_2.

Usually, it is considered that flood-assisted machining process is not environmentally friendly. However, if the environmental impacts of LN_2 are also included in the component-stage-based emissions-oriented (CSEO) model, the results could be significantly different. According to the authors' best knowledge, this is the first study to analyze the impacts of LN_2 production on the environment. The CE per part due to LN_2 can be defined as:

$$CE_{LN_2} = CF_{LN_2} \times (t_a + t_c) \times Q_{LN_2}, \tag{14}$$

where CF_{LN_2} is the carbon factor of liquid nitrogen, t_a is an air cutting time and Q_{LN_2} is flow rate of LN_2.

- Carbon emissions due to MQL oil

Even though MQL oil is used in a minimal quantity and has low environmental impacts, it is used one time (non-recoverable) and it cannot be neglected if used in an industrial environment where the cutting processes may continue for several hours. Therefore, the *CE* per part due to MQL oil can be defined as:

$$CE_{MQL} = CE_{MQL} \times (t_a + t_c) \times Q_{MQL}. \tag{15}$$

- Carbon emissions due to emulsion

The emissions due to the application of emulsions during the machining process can be obtained as follows. Where S denotes the flow rate and consumption of emulsion and $CF_{emulsion}$ is the carbon footprints of emulsion.

$$CE_{emulsion} = CF_{emulsion} \times S. \tag{16}$$

- Carbon emissions due to cleaning

The need for cleaning in the machining process is inevitable when emulsions are used. Environmental impacts or carbon emission factor of cleaning-related activities can be found in the literature. Hence, the *CE* due to the cleaning stage is:

$$CE_{cl} = CF_{cl} \times V. \tag{17}$$

It is important to mention that CF_{cl} is a carbon factor of the cleaning process and V is volume of material removed. The units of *CF* vary according to the process.

- Carbon emissions due to disposal

ISO and some governmental organizations have stringent rules about the disposal of metalworking fluids used in the machining process. Thus, it is necessary to include the carbon emissions of the disposal stage ($CF_{disposal}$) in the system's boundary:

$$CE_{disposal} = CF_{disposal} \times S. \tag{18}$$

- CO_2 emissions indicator

Performance indicators are essential for studying the impact of the machining process on the environment. It is essential to determine the contribution of the cutting stages on the CO_2 emitted per part produced. Thus, the fraction of CE_m and carbon emission per part (CE_P), called the CO_2 emissions indicator (*CEI*). It can be defined as:

$$CEI = \frac{CE_m}{CE_P}. \tag{19}$$

- Cutting fluid distilling and condensing process CE_{dc}

It is a fact that cutting fluids are disposed of using various methods after use. Carbon emissions due to the distilling method used to dispose of the cutting fluids are measured in kilograms of CO_2 per liter.

- Spindle lubricant oil production and disposal CE_{sl}

It is important to quantify the carbon emission due to the disposal of spindle lubricants. It is also measured in kilograms of CO_2 per liter.

4.7. Water Consumption

Thousands of gallons of water (Wa) are consumed in machining workshops monthly. This water is also considered to be an important metric for evaluating sustainability. The sustainability values of water consumption for sustainable machining processes have not been included in the guidelines before. Pervaiz et. al [32] published a state-of-the-art review study on water consumption in the machining process. The guidelines can be obtained in the authors' study. The quantification of this sustainable metric is mainly obtained in terms of the quantity of water used in the workshop.

5. Energy-Integrated Heuristic Algorithm for Sustainable Machining

In the past, a bulk of published literature can be a fund which only focuses on finding the optimal cutting condition of the process [33]. Different research groups tried to find optimal cutting conditions according to specific criteria and constraints. For example, researchers found the cutting parameters according to the best machining characteristics, such as the quality of the workpiece [34]. On the other hand, a second group of scholars optimized the cutting parameters for the minimum environmental impacts of the machining process [35]. A third group tried to minimize the machining costs to get economic benefits and optimized machining parameters [15]. Similarly, cutting parameters were also optimized for the best tool design and a longer tool life. However, optimal sustainable parameters obtained by considering machinability, economic, and environmental aspects are not studied in detail for advanced machining technologies.

Thus, the purpose of the proposed algorithm was to find the optimal machining parameters and their levels by considering the sustainability indicators explained in the last section (Section 4) and also the machinability characteristics. The proposed energy-integrated heuristic algorithm for sustainable machining offers the OPAI, which indicates the performance of the whole machining process in a holistic system. The proposed algorithm can deal with all kinds of qualitative and quantitative algorithms, regardless of whether they are considered to be "the higher the better" or "the lower the better." In summary, the proposed algorithm was based on a heuristic approach and is a very useful tool for solving multi-criteria decision making (MCDM) problems in sustainable machining. The methodology used to find the sustainability values of process/products can be found in Figure 2. Several variables along with notations and explanations are explained in Table 5.

Table 5. List of the abbreviations used in the proposed algorithm.

Abbreviation	Definition	Abbreviation	Definition
n	Experiment number	m	Metrics counter
l	Cutting parameters level counter	i	Indicator counter
z	Machining response counter	N	Total number of experiments
M	Machining quality characteristics or total responses	NM	Number of studied metrics
N_k	Selection of the indicator for each response	I_{mi}	Values of the sustainability indicator (i)
Mr_z	Values of each machining response (z)	W_z	Weight for responses (z)
W_m	Weight for sustainable metrics	W_i	Weight for indicator
SF_{minz}	Sustainability factor for each experiment number (n)	SI_{minz}	Sustainability index for each experiment no. (n)
WSI_{minz}	Weighted sustainability index for each cutting test (n)	OPI_n	Overall performance assessment indicator

- Step 1: Calculation of the sustainability factor (SF_{minz})

In the first step, experimental cutting test results are used along with sustainability indicators to get sustainability factors. Equations (20) and (21) define the sustainability factors. If each machining response (Mr_z) and sustainability indicator (I_{mi}) have the same status, i.e., the lower the better or the higher the better, then the sustainability factor can be obtained as follows:

$$SF_{minz} = I_{im} \times Mr_z. \tag{20}$$

However, if the machining response and sustainability indicator have opposite statuses, i.e., one is the higher the better, and the other is the lower the better, it can be calculated as follows:

$$SF_{minz} = \frac{Mr_z}{I_{im}}. \tag{21}$$

- Step 2: Calculation of the sustainability index (SI_{minz})

Sustainability factors for each experimental test are calculated. From the sustainability factors, the optimal sustainability factors are calculated and used to find the sustainability index of each test. In this step, normalization or scaling of each response is performed. If SF_{minz} is based on the lower the better, the sustainability index can be defined as:

$$SI_{minz} = \frac{Min(SF_{minz})}{Max(SF_{minz})}. \tag{22}$$

However, if SF_{minz} is based on the higher the better, the sustainability index can be defined as:

$$SI_{minz} = \frac{SF_{minz}}{Max\ SF_{minz}}. \tag{23}$$

It is worth mentioning that the maximum value of SI_{minz} will be 1. Once the SI_{minz}'s are obtained, different weights can be assigned to calculate the weighted sustainability index.

- Step 3: Calculation of the weighted sustainability index (WSI_{kpin})

Weights are assigned to the obtained SI_{minz}'s, where the weight assignments are highly dependent upon the user's choice. Sometimes, all responses are considered equally; however, in industrial applications, some metrics are considered to be more important than others. For example, for aerospace- and defense-related products, surface quality is considered to be the most important metric compared to energy consumption. Weights can also be assigned according to expert opinion. In this work, the grey entropy method [36] was used to calculate the weights for SI_{minz}:

$$WSI_{minz} = W_m \times W_z \times W_i \times SI_{kpjn}. \tag{24}$$

- Step 4: Calculation of the total weighted sustainability index (WSI_{kpin})

The last step of the algorithm is to calculate the total weighted sustainability index. It can be calculated using Equation (25):

$$OPI_n = \sum_{m=1}^{NM} \times \sum_{i=1}^{N_m} \times \sum_{z=1}^{M} \times WSI_{minz}. \tag{25}$$

6. Assessment Model Validation (Case Studies)

The proposed algorithm was validated using three case studies published by the current authors in the field of machining (external turning and milling) processes. The three case studies were chosen from MQL, nanofluid-based small quantity cooling lubrication SQCL, and cryogenic-assisted cooling approaches. The process parameters included the cutting speed, depth of cut, feed rate, and cooling mechanism. The optimal cutting parameters for the process were also found using the Non-Dominated Sorting Genetic Algorithm NSGA-II algorithm.

The OPAI was calculated to find the optimal and sustainable cutting parameters. The idea was to make sure the optimal conditions found from the proposed algorithm were consistent with the physical findings of the previous study.

6.1. Case Study 1: Nanofluid SQCL Assisted Milling Process

In general, the case studies consisted of input process parameters, such as the feed rate, spindle speed, depth and width of the cut, and cooling technique. Similarly, machinability responses, such as the material removal rate, tool life, surface quality, and power and energy consumption were considered. In industrial environments, indicators are mostly given various weights according to their importance. However, in the present study, the authors assigned equal weights to avoid redundancy. In the selected case study [36], face milling experiments were performed on a CNC machine tool with a spindle power of 5.6 kW and a maximum rotation speed of 6000 rpm. AISI-1045 steel was used as the work material. Surface roughness, material removal volume, and cutting energy were considered as three machining responses. The proposed algorithm was implemented to find the optimal cutting parameters based on the following assumptions:

- Environment, economy, and society (operator health and safety) were selected as three metrics.
- The sustainability indicator for the cost was the energy cost.
- The sustainability indicator for the environment was the CO_2 emissions due to the electricity consumed by the machine tools.
- The sustainability indicators for the personal health and operation safety metric were OS_c, OS_{hsc}, and OS_{hec}.

The OPAI was calculated using the steps of the algorithms mentioned in Section 4. All the calculations are mentioned in Appendices A–C. These three appendices are only related to the first case study. The number 27 shows the total number of experiments. Appendices A–C are designed to provide the calculations of the sustainability factors, calculations of *SI*, and the calculations of the *WSI*, respectively.

In the published study, only the grey relational grade (GRG) was used to find the optimal cutting parameters. However, the proposed algorithm considered both the machining and sustainability indicators simultaneously and found the OPAI values for the same experiments. Figure 4 shows the comparison of the OPAI with the GRG. The machining parameters used in this test were as follows: a spindle speed of 1200 rev/min, a feed rate of 320 mm/min, a depth of cut of 0.5 mm, and a width of cut of 15 mm. The following output responses were achieved: Material Removal Rate MRR of 2400 mm^3/min, Surface Roughness SR of 2.29, and cutting energy of 53.98 kJ. Similarly, the lowest OPAI was found for the experimental conditions of test 9, and the GRG was also found to be the lowest for the same cutting conditions. In this case study, the proposed algorithm predicted the identical cutting parameters for both the best and worst outcomes. The predictions for identical cutting parameters can be explained because very few indicators were selected for simplicity. However, the proposed algorithm can also predict different optimal cutting conditions, where this validation is left for future work. The idea was to open a new research direction and to integrate the sustainability indicators with the machining response to perform a holistic analysis.

6.2. Case Study 2: Lubricooling-Assisted Approaches for the Turning Process

Jamil et al. [3] conducted external turning experiments on a Ti-6Al-4V workpiece under hybrid alumina carbon-nanotubes Al_2O_3-CNT nanofluids and cryogenic cooling. The process parameter includes the depth of cut, cutting speed, feed rate, and cooling and lubrication approach. The cutting forces, temperature, and surface quality of the workpiece were measured to assess the performance of the lubricooling approaches. Two machining responses, namely, cutting forces and surface roughness, and four sustainability indicators, namely, cumulative energy demand (CED), carbon emission, production cost, and personal health index were considered as the responses in the algorithm. The design of the experiment and cutting conditions are shown in Table 3 of [3]. The OPAI of both lubricooling-assisted machining processes was calculated according to the steps mentioned in Section 5. The highest OPAI values of both lubricooling approaches were found at a cutting speed of 150 m/min and a feed rate of

0.2 mm/rev (Figure 5). Thus, it can be said that the machining of titanium alloys with cutting conditions of experiment 9 of the case study [3] was optimal and the most sustainable.

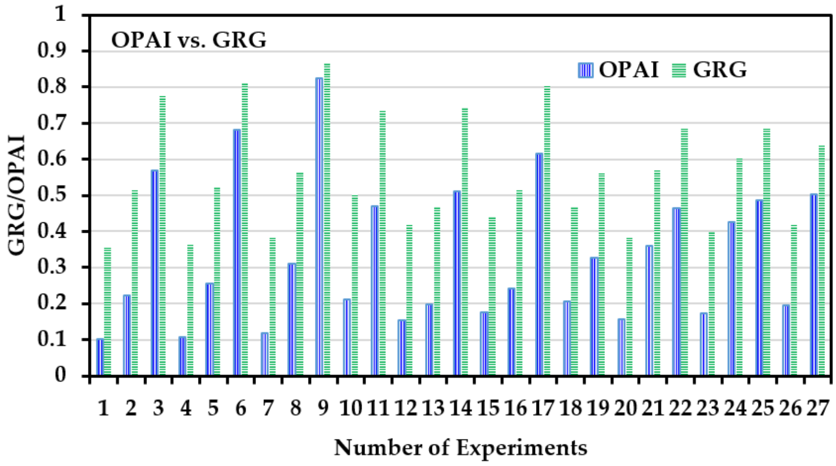

Figure 4. Comparison of the Overall Performance Assessment Indicator (OPAI) and the grey relational grade (GRG) for case study 1.

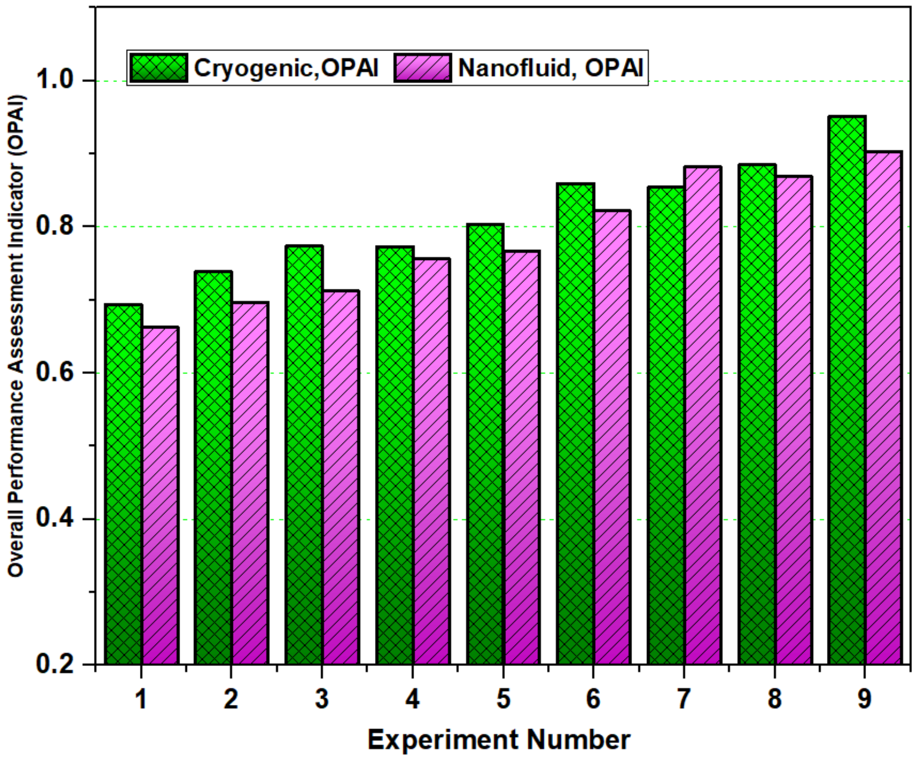

Figure 5. Calculation of the Overall Performance Assessment Indicator for case study 2.

6.3. Case Study 3: Cryogenic-Assisted Machining Process

Khan et al. [36] conducted three sets of experiments on various lubricooling (MQL, flood, and cryogenic) approaches to investigate their sustainability. The tool life and surface quality were measured as the studied machining quality characteristics. The cumulative energy demand, carbon emissions, production cost, and personal health index were measured as the sustainability indicators. Several sustainability factors (mentioned in Section 4.2) for energy consumption, cost, and carbon emission were included. The presented assessment algorithm was employed to evaluate the optimal cutting conditions that satisfied both the machining and sustainability characteristics.

The OPAI of each lubricooling approach was calculated and shown in Figure 6. It was noted that the highest value of OPAI (i.e., 1) was obtained in experimental trial number 1 [36]. The experiment was performed at a cutting speed of 30 m/min, a feed rate of 0.1 mm/min, and a depth of cut of 0.8 mm using an MQL-assisted lubrication approach. The cutting tool wore quickly at higher cutting speeds; thus, the OPAI decreased from lower to higher cutting conditions.

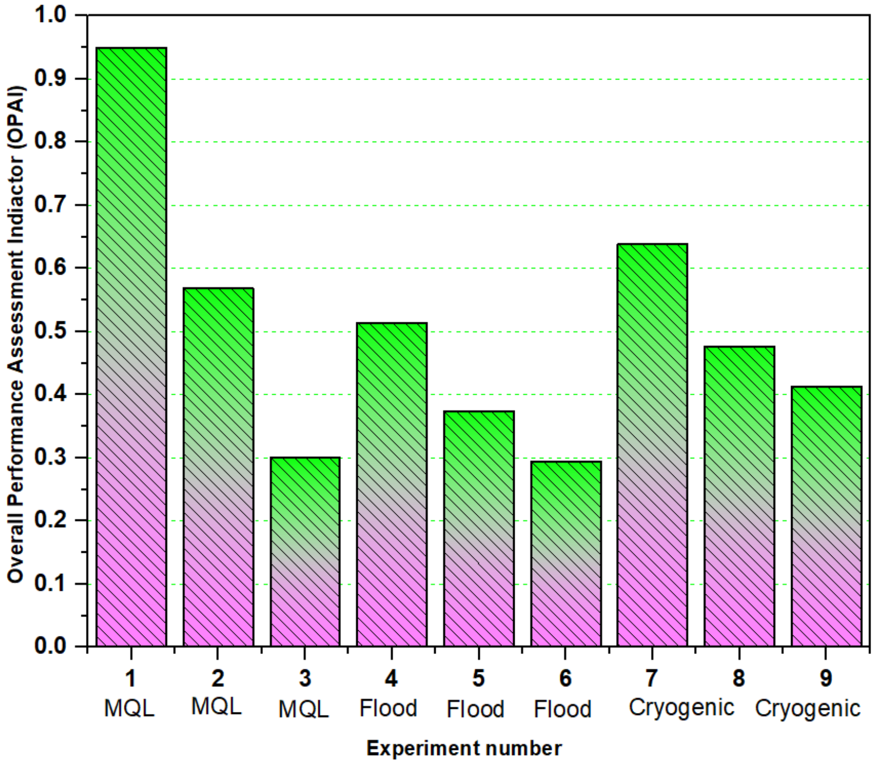

Figure 6. Weighted sustainability index of cryogenic LN_2-assisted machining for case study 3.

7. Conclusions

In the present work, holistic sustainable guidelines were developed for cryogenic- and nanofluid-assisted MQL machining processes. Based on the guidelines, a heuristic algorithm was proposed, which not only addressed sustainability metrics but also incorporated the machinability characteristics. A set of new optimal cutting parameters were found based on both the machinability (measured in case studies) and sustainability indicators (added in the algorithm).

Seven major sustainability metrics (time, electric power, energy, cost, emission, waste, and water consumption) were considered in the proposed algorithm. From the sustainable guidelines, several indicators were evaluated under each metric.

A novel assessment indicator named the Overall Performance Assessment Indicator was introduced and verified from three different case studies. The results obtained from the first case study were in good agreement with the experimental results of the case study. In the second and third case studies, the optimal cutting parameters were found for the machinability and sustainability perspectives simultaneously. The proposed OPAI indicator was found to be extremely useful for achieving optimization in the mechanical machining processes.

Limitation and Future Trends

There are some challenges that should be dealt with in the future. The qualitative indicators under sustainability guidelines received a specific quantitative score, which may vary in different industrial environments. Efforts should be made to make a unique score assignment mechanism. Second, data for some indicators, such as the fixture life or the cost incurred when disposing of chips were not available in detail, and manufacturers also lacked this type of data. This emphasizes the need for proper and detailed data collection to perform a holistic analysis. Another issue is that the influence of energy consumption on the economy and environment will vary from country to country. The price of electricity and the type of natural resources used to produce electricity are major factors that decide the impact.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. OPAI Step 1: Calculation of the sustainability factors.

No.	Sustainability Factor for MRR					Sustainability Factor for Ra					Sustainability Factor for Energy				
	MRR×CE	MRRCost	MRR×Ostc	MRR×Oshss	MRR×Wf	Ra×CE	Ra×Cost	Ra×Ostc	Ra×Oshss	Ra×Wf	Energy×CE	Energy×Cost	Energy×Ostc	Energy×Oshss	Energy×Wf
1	0.0004	0.3247	0.0030	0.0091	0.0030	0.4562	353.6293	3.3000	9.9000	3.3000	74.0676	57,416.7566	535.8020	1607.4060	535.8020
2	0.0001	0.0420	0.0011	0.0034	0.0011	0.1407	109.1081	2.9500	8.8500	2.9500	8.8233	6839.7470	184.9290	554.7870	184.9290
3	0.0000	0.0107	0.0006	0.0018	0.0006	0.0322	24.9624	1.4100	4.2300	1.4100	2.0216	1567.1227	88.5190	265.5570	88.5190
4	0.0003	0.2104	0.0025	0.0074	0.0025	0.4211	326.3995	3.8300	11.4900	3.8300	46.8448	36,313.7760	426.1090	1278.3270	426.1090
5	0.0000	0.0270	0.0009	0.0028	0.0009	0.1458	113.0427	3.8700	11.6100	3.8700	5.5033	4266.1205	146.0500	438.1500	146.0500
6	0.0000	0.0069	0.0005	0.0015	0.0005	0.0303	23.4605	1.6800	5.0400	1.6800	1.2578	975.0503	69.8230	209.4690	69.8230
7	0.0002	0.1508	0.0021	0.0063	0.0021	0.3706	287.2946	3.9700	11.9100	3.9700	33.7780	26,184.4792	361.8320	1085.4960	361.8320
8	0.0000	0.0192	0.0008	0.0023	0.0008	0.1120	86.8211	3.5300	10.5900	3.5300	3.9018	3024.6193	122.9760	368.9280	122.9760
9	0.0000	0.0045	0.0004	0.0013	0.0004	0.0319	24.7265	2.2900	6.8700	2.2900	0.7520	582.9408	53.9880	161.9640	53.9880
10	0.0001	0.1021	0.0015	0.0030	0.0015	0.1574	122.0092	1.8100	3.6200	1.8100	29.3081	22,719.4620	337.0420	674.0840	337.0420
11	0.0000	0.0216	0.0008	0.0015	0.0008	0.0416	32.2563	1.1300	2.2600	1.1300	5.2557	4074.1993	142.7270	285.4540	142.7270
12	0.0001	0.1087	0.0018	0.0036	0.0018	0.2677	207.5275	3.4700	6.9400	3.4700	23.0702	17,883.9078	299.0310	598.0620	299.0310
13	0.0001	0.0666	0.0012	0.0025	0.0012	0.1982	153.6743	2.8500	5.7000	2.8500	18.7531	14,537.2634	269.6040	539.2080	269.6040
14	0.0000	0.0140	0.0006	0.0012	0.0006	0.0413	32.0487	1.4100	2.8200	1.4100	3.3323	2583.1736	113.6480	227.2960	113.6480
15	0.0001	0.0707	0.0015	0.0030	0.0015	0.2406	186.4882	3.9100	7.8200	3.9100	14.6727	11,374.1605	238.4760	476.9520	238.4760
16	0.0001	0.0445	0.0010	0.0021	0.0010	0.1405	108.9151	2.5500	5.1000	2.5500	11.7667	9121.4893	213.5590	427.1180	213.5590
17	0.0000	0.0096	0.0005	0.0010	0.0005	0.0332	25.7292	1.3900	2.7800	1.3900	2.2099	1713.1375	92.5510	185.1020	92.5510
18	0.0001	0.0483	0.0013	0.0025	0.0013	0.2053	159.1218	4.1200	8.2400	4.1200	9.6211	7458.2172	193.1090	386.2180	193.1090
19	0.0001	0.0494	0.0010	0.0010	0.0010	0.1109	85.9947	1.7600	1.7600	1.7600	15.3985	11,936.7912	244.3030	244.3030	244.3030
20	0.0002	0.1935	0.0023	0.0023	0.0023	0.3658	283.5808	3.3300	3.3300	3.3300	46.7762	36,260.6170	425.7970	425.7970	425.7970
21	0.0000	0.0301	0.0009	0.0009	0.0009	0.1008	78.1726	2.3600	2.3600	2.3600	7.0769	5485.9969	165.6200	165.6200	165.6200
22	0.0000	0.0319	0.0008	0.0008	0.0008	0.0585	45.3817	1.1700	1.1700	1.1700	9.7040	7522.4671	193.9390	193.9390	193.9390
23	0.0002	0.1254	0.0019	0.0019	0.0019	0.3250	251.9028	3.7200	3.7200	3.7200	29.5760	22,927.1478	338.5790	338.5790	338.5790
24	0.0000	0.0195	0.0007	0.0007	0.0007	0.0874	67.7730	2.5800	2.5800	2.5800	4.4508	3450.1967	131.3430	131.3430	131.3430
25	0.0000	0.0223	0.0007	0.0007	0.0007	0.0585	45.3699	1.4100	1.4100	1.4100	6.6782	5176.8610	160.8860	160.8860	160.8860
26	0.0001	0.0896	0.0016	0.0016	0.0016	0.2857	221.4482	3.8600	3.8600	3.8600	21.2290	16,456.5845	286.8500	286.8500	286.8500
27	0.0000	0.0135	0.0006	0.0006	0.0006	0.0770	59.6971	2.7600	2.7600	2.7600	3.0175	2339.1547	108.1470	108.1470	108.1470

Appendix B

Table A2. OPAI Step 2: Calculation of the sustainability index.

No.	Sustainability Index														
	MRR×CE	MRR×Cost	MRR×Ostc	MRR×Oshss	MRR×Wf	Ra×CE	Ra×Cost	Ra×Ostc	Ra×Oshss	Ra×Wf	Energy×CE	Energy×Cost	Energy×Ostc	Energy×Oshss	Energy×Wf
1	0.0139	0.0139	0.1375	0.0688	0.1375	0.0663	0.0663	0.3424	0.1182	0.3424	0.0102	0.0102	0.1008	0.0673	0.1008
2	0.1070	0.1070	0.3667	0.1833	0.3667	0.2150	0.2150	0.3831	0.1322	0.3831	0.0852	0.0852	0.2919	0.1949	0.2919
3	0.4193	0.4193	0.6875	0.3438	0.6875	0.9398	0.9398	0.8014	0.2766	0.8014	0.3720	0.3720	0.6099	0.4072	0.6099
4	0.0214	0.0214	0.1688	0.0844	0.1688	0.0719	0.0719	0.2950	0.1018	0.2950	0.0161	0.0161	0.1267	0.0846	0.1267
5	0.1663	0.1663	0.4500	0.2250	0.4500	0.2075	0.2075	0.2920	0.1008	0.2920	0.1366	0.1366	0.3697	0.2468	0.3697
6	0.6524	0.6524	0.8438	0.4219	0.8438	1.0000	1.0000	0.6726	0.2321	0.6726	0.5979	0.5979	0.7732	0.5163	0.7732
7	0.0298	0.0298	0.2000	0.1000	0.2000	0.0817	0.0817	0.2846	0.0982	0.2846	0.0223	0.0223	0.1492	0.0996	0.1492
8	0.2341	0.2341	0.5333	0.2667	0.5333	0.2702	0.2702	0.3201	0.1105	0.3201	0.1927	0.1927	0.4390	0.2931	0.4390
9	1.0000	1.0000	1.0000	0.5000	1.0000	0.9488	0.9488	0.4934	0.1703	0.4934	1.0000	1.0000	1.0000	0.6677	1.0000
10	0.0440	0.0440	0.2750	0.2063	0.2750	0.1923	0.1923	0.6243	0.3232	0.6243	0.0257	0.0257	0.1602	0.1604	0.1602
11	0.2080	0.2080	0.5500	0.4125	0.5500	0.7273	0.7273	1.0000	0.5177	1.0000	0.1431	0.1431	0.3783	0.3789	0.3783
12	0.0414	0.0414	0.2292	0.1719	0.2292	0.1130	0.1130	0.3256	0.1686	0.3256	0.0326	0.0326	0.1805	0.1808	0.1805
13	0.0676	0.0676	0.3375	0.2531	0.3375	0.1527	0.1527	0.3965	0.2053	0.3965	0.0401	0.0401	0.2002	0.2006	0.2002
14	0.3207	0.3207	0.6750	0.5063	0.6750	0.7320	0.7320	0.8014	0.4149	0.8014	0.2257	0.2257	0.4750	0.4758	0.4750
15	0.0637	0.0637	0.2813	0.2109	0.2813	0.1258	0.1258	0.2890	0.1496	0.2890	0.0513	0.0513	0.2264	0.2267	0.2264
16	0.1011	0.1011	0.4000	0.3000	0.4000	0.2154	0.2154	0.4431	0.2294	0.4431	0.0639	0.0639	0.2528	0.2532	0.2528
17	0.4667	0.4667	0.8000	0.6000	0.8000	0.9118	0.9118	0.8129	0.4209	0.8129	0.3403	0.3403	0.5833	0.5843	0.5833
18	0.0932	0.0932	0.3333	0.2500	0.3333	0.1474	0.1474	0.2743	0.1420	0.2743	0.0782	0.0782	0.2796	0.2800	0.2796
19	0.0912	0.0912	0.4125	0.6188	0.4125	0.2728	0.2728	0.6420	0.6648	0.6420	0.0488	0.0488	0.2210	0.4427	0.2210
20	0.0232	0.0232	0.1833	0.2750	0.1833	0.0827	0.0827	0.3393	0.3514	0.3393	0.0161	0.0161	0.1268	0.2540	0.1268
21	0.1494	0.1494	0.4583	0.6875	0.4583	0.3001	0.3001	0.4788	0.4958	0.4788	0.1063	0.1063	0.3260	0.6530	0.3260
22	0.1409	0.1409	0.5063	0.7594	0.5063	0.5170	0.5170	0.9658	1.0000	0.9658	0.0775	0.0775	0.2784	0.5576	0.2784
23	0.0359	0.0359	0.2250	0.3375	0.2250	0.0931	0.0931	0.3038	0.3145	0.3038	0.0254	0.0254	0.1595	0.3194	0.1595
24	0.2312	0.2312	0.5625	0.8438	0.5625	0.3462	0.3462	0.4380	0.4535	0.4380	0.1690	0.1690	0.4110	0.8234	0.4110
25	0.2013	0.2013	0.6000	0.9000	0.6000	0.5171	0.5171	0.8014	0.8298	0.8014	0.1126	0.1126	0.3356	0.6722	0.3356
26	0.0502	0.0502	0.2667	0.4000	0.2667	0.1059	0.1059	0.2927	0.3031	0.2927	0.0354	0.0354	0.1882	0.3770	0.1882
27	0.3328	0.3328	0.6667	1.0000	0.6667	0.3930	0.3930	0.4094	0.4239	0.4094	0.2492	0.2492	0.4992	1.0000	0.4992

Appendix C

Table A3. OPAI Step 3: Calculation of the weighted sustainability index.

No.	Weighted Sustainability Index														
	MRR×CE	MRR×Cost	MRR×Ostc	MRR×Oshss	MRR×Wf	Ra×CE	Ra×Cost	Ra×Ostc	Ra×Oshss	Ra×Wf	Energy×CE	Energy×Cost	Energy×Ostc	Energy×Oshss	Energy×Wf
1	0.0008	0.0008	0.0084	0.0042	0.0084	0.0040	0.0040	0.0207	0.0071	0.0207	0.0008	0.0008	0.0079	0.0053	0.0079
2	0.0065	0.0065	0.0224	0.0112	0.0224	0.0130	0.0130	0.0232	0.0080	0.0232	0.0067	0.0067	0.0229	0.0153	0.0229
3	0.0256	0.0256	0.0420	0.0210	0.0420	0.0568	0.0568	0.0485	0.0167	0.0485	0.0292	0.0292	0.0479	0.0320	0.0479
4	0.0013	0.0013	0.0103	0.0052	0.0103	0.0043	0.0043	0.0178	0.0062	0.0178	0.0013	0.0013	0.0099	0.0066	0.0099
5	0.0102	0.0102	0.0275	0.0137	0.0275	0.0126	0.0126	0.0177	0.0061	0.0177	0.0107	0.0107	0.0290	0.0194	0.0290
6	0.0398	0.0398	0.0515	0.0258	0.0515	0.0605	0.0605	0.0407	0.0140	0.0407	0.0469	0.0469	0.0607	0.0405	0.0607
7	0.0018	0.0018	0.0122	0.0061	0.0122	0.0049	0.0049	0.0172	0.0059	0.0172	0.0017	0.0017	0.0117	0.0078	0.0117
8	0.0143	0.0143	0.0326	0.0163	0.0326	0.0163	0.0163	0.0194	0.0067	0.0194	0.0151	0.0151	0.0345	0.0230	0.0345
9	0.0610	0.0610	0.0610	0.0305	0.0610	0.0574	0.0574	0.0298	0.0103	0.0298	0.0785	0.0785	0.0785	0.0524	0.0785
10	0.0027	0.0027	0.0168	0.0126	0.0168	0.0116	0.0116	0.0378	0.0195	0.0378	0.0020	0.0020	0.0126	0.0126	0.0126
11	0.0127	0.0127	0.0336	0.0252	0.0336	0.0440	0.0440	0.0605	0.0313	0.0605	0.0112	0.0112	0.0297	0.0297	0.0297
12	0.0025	0.0025	0.0140	0.0105	0.0140	0.0068	0.0068	0.0197	0.0102	0.0197	0.0026	0.0026	0.0142	0.0142	0.0142
13	0.0041	0.0041	0.0206	0.0155	0.0206	0.0092	0.0092	0.0240	0.0124	0.0240	0.0031	0.0031	0.0157	0.0157	0.0157
14	0.0196	0.0196	0.0412	0.0309	0.0412	0.0443	0.0443	0.0485	0.0251	0.0485	0.0177	0.0177	0.0373	0.0374	0.0373
15	0.0039	0.0039	0.0172	0.0129	0.0172	0.0076	0.0076	0.0175	0.0090	0.0175	0.0040	0.0040	0.0178	0.0178	0.0178
16	0.0062	0.0062	0.0244	0.0183	0.0244	0.0130	0.0130	0.0268	0.0139	0.0268	0.0050	0.0050	0.0198	0.0199	0.0198
17	0.0285	0.0285	0.0488	0.0366	0.0488	0.0551	0.0551	0.0492	0.0255	0.0492	0.0267	0.0267	0.0458	0.0459	0.0458
18	0.0057	0.0057	0.0203	0.0153	0.0203	0.0089	0.0089	0.0166	0.0086	0.0166	0.0061	0.0061	0.0219	0.0220	0.0219
19	0.0056	0.0056	0.0252	0.0378	0.0252	0.0165	0.0165	0.0388	0.0402	0.0388	0.0038	0.0038	0.0173	0.0348	0.0173
20	0.0014	0.0014	0.0112	0.0168	0.0112	0.0050	0.0050	0.0205	0.0212	0.0205	0.0013	0.0013	0.0100	0.0199	0.0100
21	0.0091	0.0091	0.0280	0.0420	0.0280	0.0182	0.0182	0.0290	0.0300	0.0290	0.0083	0.0083	0.0256	0.0513	0.0256
22	0.0086	0.0086	0.0309	0.0464	0.0309	0.0313	0.0313	0.0584	0.0605	0.0584	0.0061	0.0061	0.0219	0.0438	0.0219
23	0.0022	0.0022	0.0137	0.0206	0.0137	0.0056	0.0056	0.0184	0.0190	0.0184	0.0020	0.0020	0.0125	0.0251	0.0125
24	0.0141	0.0141	0.0343	0.0515	0.0343	0.0209	0.0209	0.0265	0.0274	0.0265	0.0133	0.0133	0.0323	0.0646	0.0323
25	0.0123	0.0123	0.0366	0.0549	0.0366	0.0313	0.0313	0.0485	0.0502	0.0485	0.0088	0.0088	0.0263	0.0528	0.0263
26	0.0031	0.0031	0.0163	0.0244	0.0163	0.0064	0.0064	0.0177	0.0183	0.0177	0.0028	0.0028	0.0148	0.0296	0.0148
27	0.0203	0.0203	0.0407	0.0610	0.0407	0.0238	0.0238	0.0248	0.0256	0.0248	0.0196	0.0196	0.0392	0.0785	0.0392

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