Sustainable μECM *machining process* : *indicators and assessment*

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Abstract

Sustainability assessment of a manufacturing process is not an easy task and requires knowledge from inside of the process physics or chemistry as well as the overall process performance considering the effectiveness of the process and specific applications. Sustainability assessment is with increasing demand among the manufacturing companies. At present sustainability is considered only among the traditional manufacturing techniques and non-traditional processes do not receive enough attention in spite of the increasing demand for their use. Additionally micro and nano non-traditional manufacturing processes are nearly not considered in the studies for sustainability; and micro electrochemical machining (μECM) was not an exemption either. μECM is one of the promising non-conventional machining processes but its expensive structure, complex nature of the electrochemical reaction and process dependency on operator experiences has kept it back at research level. Securing a place for a new manufacturing process has to be done by proving its sustainability in comparison to the other existing processes.In this work, the aim is to establish a framework for assessment of the μECM sustainability based on five dimensions of the sustainability in order to justify its use and the initial investment cost. Indicators and measures for the effectiveness of the process are suggested as well as machining performance parameters are discussed . Routes for optimizing machining parameters is also explored. Finally the full picture sustainability assessment is generated.

Keywords: Sustainability, Sustainable μECM, optimization, Energy consumption, Waste management, Cost management

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1. Introduction

The 21st Century has brought with it unwanted gifts to the society, including: climate change, environmental pollution and natural resources declines due to global industrialization and increased consumption. All this, together with financial crashes and business competition, has put extra pressure on manufacturing industries to maintain their role and to cope with current and future difficulties.

Manufacturing industries are one of the biggest consumers of natural resources and massive producers of by-products and wastes. They are at the center of global criticism, in particular, regarding concerns about sustainable performance. Hence, these industries are facing a major challenge to improve their performance in addition to improving their products. There are international organizations responsible for putting measures in place and providing robust indicators for assessing performance and sustainability which is the focus of this work.

The United Nations has defined sustainability development as the meeting of present needs without compromising the ability of future generations to meet their needs. That is, it has called on all organizations to advance their economic fortunes without depriving current and future global residents from a healthy environment and social equity (Cairns, 2001).

Deficiency of measurement criteria and methodologies to compare the performance of manufacturing processes with respect to sustainability has resulted in inaccurate and unreliable comparisons. However, considerable effort has been started in proposing indicators and measurement criteria for the sustainability of manufacturing processes. Also a few organizations have striven to introduce comprehensive frameworks for sustainable manufacturing indicators. As an example, the U.S. National Institute of Standards and Technology (NIST) has identified five dimensions of sustainability, including: environmental effects management; economic growth; social well-being; technological development; and performance management(Mani et al., 2013).

Currently, manufacturing industries are experiencing a lack of effective methodologies and measurement criteria with respect to the sustainability and this is worse when it comes to micro manufacturing, where there is still a huge knowledge gap in the selection and utilization of the sustainable micro manufacturing methods and technologies. This is particularly so when it comes to non-traditional machining approaches due to their performance uncertainty. In many cases, due to the lack of knowledge, standards, manufacturing and production guidelines the selection of appropriate technology and its competitiveness will be affected , which will substantially influence the sustainability of the process.

Hence, defining approved sustainability measurement criteria, methodologies and sustainability assessment technologies based on a scientific, computable and comparable model covering all manufacturing processes and methods is essential.

Any sustainability assessment has to consider three different levels, including system, process and product, with each level having its own criteria and indicators that can be assessed individually (Jayal et al., 2010).

In addition to this, there is another view when looking at any technology and is especially relevant in the case of micro-product fabrication in which intermediate parts can take up to 98% of the product component (De Grave et al., 2010) and includes:

- The final product: is the artefact that is closest to the requirement of the end-user.
- Intermediate parts: These are the parts that are not included in the final product but they use a high portion of the production resources
- The production system: it is considered as manufacturing process chain but it includes all necessary material production, recycling and disposal chain

Machining processes are important contributors to GDP in the developed countries. Also, due to the demand for shorter production life cycle and more optimized manufacturing systems, it is expected that their contribution to the economic development will increase.

1.1. Sustainability assessment of machining process

Different organizations around the world, such as the OECD (Organization for Economic Corporation and Development), ASMC (American Small Manufacturing Coalition) put effort into identifying and introducing sustainable manufacturing measurements criteria, indicators and qualitative and quantitative methods. The same applies to the machining processes, as one of the most important branches of manufacturing operations.

Currently, there are different approaches and assessment methodologies for investigating machining processes sustainability in macro manufacturing sector. Also, various standards and documents are available, but these differ from industry to industry and from one region to the other. Currently, various indicators and methods have been introduced and applied by engineers and researchers to evaluate the sustainability of the certain sectors. Simultaneously, industries and organizations are using different parameters and methods to evaluate their sustainability internally, which makes it impossible to have accurate comparable results between them. Therefore, the lack of unit classification and references adaptable to all machining sectors (research and industry) is very obvious and that felt most when it comes to micro ad nano machining processes in spite of the increased demand for micro and nano scale products.

The common perspective in all the available definitions and documents is the development of sustainable manufacturing by protection of the natural resources and raw materials, maintaining environmental conditions suitable for human beings lives and fulfillment of economic, customer and employees demands. Accordingly, manufacturing industries, including machining industries, are expected to align their activities with the three main aspects of sustainability, namely, economy, environment and society (Heilala et al., 2015) and (Álvarez et al., 2017) . These three aspects can be extended at a more detailed level to include cost management, energy consumption, waste management, environmental impact and finally, health and safety. The most commonly deployed model or framework observed in the industries is presented in figure 1 which forms the foundation of the research in this work.

Most researches have been concentrated on the assessment of traditional machining operations, including drilling, milling, turning and grinding(Kim et al., 2012), hence there have been very little non-tradition machining sustainability assessment. The general approach towards sustainability of machining operations has been based on assessment of the environmental impact of the process and subsequently, other dimensions have been assessed have been assessed with regards to environmental impact. Although this is unrealistic due to interrelation between sustainability dimensions but this approach does not give a full picture of existing correlation between them and limits the challenge to one dimension interrelation with the others.

The micro machining process itself is very complicated and very much dependent on operator experience or it is a database oriented process, which means that it is very hard to apply unique approach to a variety of materials. Hence, it is necessary to consider each material and its final products individually, which prevents to apply a unique sustainability framework to

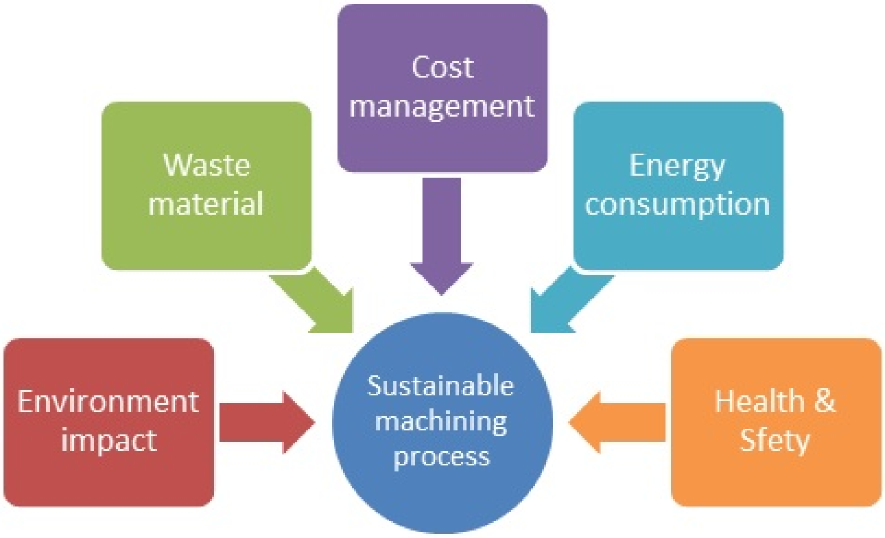

Figure 1: Elements of machining process sustainability

the process. Most of the available academic research in the area of sustainable machining operations is based on specific initial conditions, materials, methods and products, with there being no comprehensive assessment model widely used in this context. The limited research based on a general approach towards machining sustainability found in the literature is outlined below.The literature shows a rise in research focusing on micro manufacturing in recent years but not yet on non- conventional micro manufacturing.

Hegab et al. (Hegab et al., 2018b)proposed and discussed a sustainability assessment algorithm for machining processes based on machining quality characteristics and sustainable machining metrics results in order to find the optimum parameters. They used weighting factors for the measured process outputs, metrics and indicators, which made the algorithm flexible and applicable to any experimental case. Also, they (Hegab et al., 2018a) conducted an experimental work to provide the optimized process parameters for machining Inconel 718 with Multi-walled carbon nanotubes and Al2O3 nanofluidics. They studied power consumption, environmental impact (CO2) and personal health and operational safety as sustainability dimensions and they used average surface roughness and flank wear as investigated machining outputs. Alvarez et al. (Álvarez et al., 2017) reviewed over 300 publications in the area of sustainable manufacturing engineering with the focus being on machining and they summarized published works in order to propose a unified framework, including the existing parameters and new ones, aimed at achieving integral sustainability in machining. Priarone et al.(Priarone et al., 2018) described an approach to integrate the environmental and economic assessment of the machining process. Their work and assessment is based on considering one source (energy) and one type of environmental impact (CO2 emissions), suggesting that the range of process parameters that allow for maximum efficiency is influenced by material machinability. However, all of the above research was aimed at traditional machining.

Gamage et al.(Gamage and DeSilva, 2015) extensive qualitative research in 2012 revealed that only 25 publications were concerned directly or indirectly with non-traditional machining operations sustainability. The figure below shows the distribution of these research endeavors on different areas of non-traditional machining methods. As it is clear, nearly half of the publications were investigated the EDM (Electric Discharge Machining) and only %10 of the publications were related to ECM.

That reveals the wide gap between the sustainability assessment state of art in non-traditional and traditional machining field in spite of the importance of the contribution of the manufacturing sector in the economy, which was estimated as 7000 billion of turnover in 2012(Gamage and DeSilva, 2015).

Knowing this statistics and being aware that non-traditional machining operations at the micro and nano scale are much younger than the traditional form,extending sustainability assessment work to these areas would help to develop them.

2. Sustainability of μECM

One of the main tools in machining sustainability assessments is known as Life-cycle assessment, which believes to be the main tool for the environmental assessment of the products and it has been developed to cover the analysis and assessment of the environmental impact of the product through its whole life cycle including resources, production and disposal(De Grave et al., 2010). This requires to consider all involved functions and processes in the life of the product; and this is providing the required assessments for the important aspects of sustainability assessment. Therefore, product sustainability assessment is a life-cycle assessment from design to production and

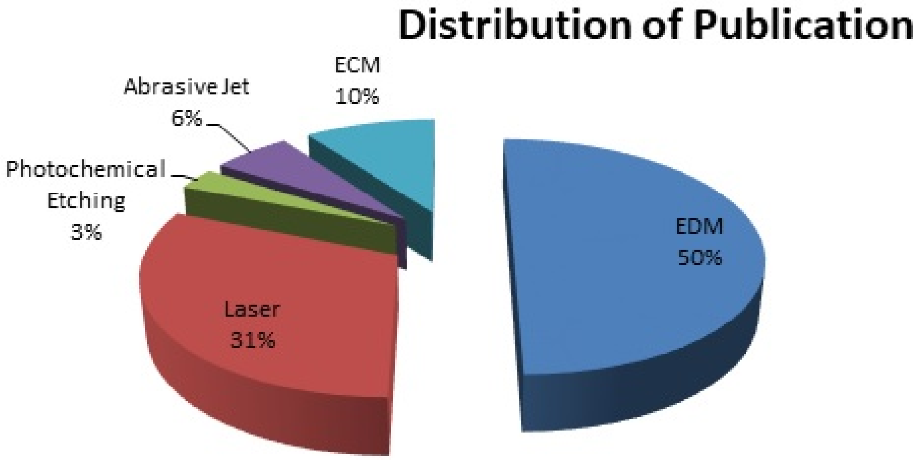

Figure 2: Distribution of 25 publications between different non-traditional machining methods (Gamage and DeSilva, 2015)

from consumption to the end of the life treatment; hence having a sustainable process is one of the requirements of product sustainability features.

The importance of sustainability assessment of machining methods, has motivated researchers around the world to experience new findings in this field by introducing new methodologies and experimental works in addition to the life-cycle assessment.

Krolczyk et al (Krolczyk et al., 2019) provided a comprehensive review in machining processes of hard-to-cut materials with the focus on the improvement of the processes considering reduction of pollution generated by coolants and emulsions. The target machining processes were dry cutting, MQL/MQCL, cryogenic cooling, high pressure coolant and biodegradable vegetable oil. The approach was to minimize the total cost, cutting force, energy consumption and temperature but to improve the surface quality, removed materials and tool life. Also the influence on operators health and impact on environmental areas were considered and finally the cutting parameters and cutting tool specifications to achieve sustainable development were analyzed and discussed.

The field of non-conventional micro machining needs strongly such an effort and investigation. Despite the importance of micro machining industry and its increased applications in industrial state of the art, there has not been much publication in the area of sustainable micro machining technologies, particularly non-conventional one. As a result, there has been little research in the field of μECM sustainability assessment.

Kellans et al.(Kellens et al., 2013) discussed the environmental impact of non-conventional processes, whilst Tristo et al.(Tristo et al., 2015) presented and analyzed the online energy consumption in micro EDM and Modica et al. (Modica et al., 2011) discussed the sustainable micro manufacturing of micro components for micro EDM and there has been a recent publication of the author(Mortazavi and Ivanov, 2017) considering the μECM process. This researcher is not aware of any other publications that discuss μECM sustainability assessment.

As mentioned, sustainability of μECM should be assessed within the five dimensions illustrated in figure 1. μECM is still a young research field and most investigation has been based on experimental works and case studies that cannot be easily generalized for a diverse domain. Before continuing this section, it is important to highlight three fundamental grounds relating to the sustainability assessment of non-traditional machining, in general and μECM, in particular.

- Non-traditional machining methods are known as alternative methods for machining and yet to be recognized as the main method (with the exception of special cases). In addition to this, the choice of different applicable non-traditional methods on a production line is mainly based on operator experience or a trial and error approach. Both these conditions would add extra complexity to the sustainability assessment of a machining operation as operator experience can influence the methodology and the performance significantly.This means that the sustainability of any selected method should be compared with other machining methods, to determine whether more than one approach is applicable and acceptable.

- As briefly mentioned, the five dimensions of sustainability assessment are in a complex inter-relationship, which needs to be considered for any process. These criteria can present direct or indirect/ qualitative or quantitative impacts on each other, and hence, need to be considered in detail in order to obtain accurate comprehensive results.

- The performance of dimensional sustainability of the process should

> be analyzed quantitatively and qualitatively using the relevant indicators. Different organizations have introduced a list of indicators. The indicators developers have used different methodologies in establishing these. However, generally, the main purpose of these frameworks is for external reporting to the stakeholders, rather than being used for decision making and optimization of the operations. Hence, it is vital to acknowledge that the aim of assessment of the sustainability performance should be not only to present more interesting reports to the stakeholders, but also to help to improve and optimize the operation.

The rest of this paper will focus on general features of the indicators, which is followed by the introduction of possible metrics and indicators for μECM sustainability assessment. In section 3, will give a brief discussion on proposed approach in comparison with other approach, two case studies will be introduced in section 4 and finally, the results of this research are considered and suggestions for the future work put forward.

2.1. Sustainability indicators

The robustness of the sustainability framework is very much dependent on the selection of indicators and metrics and their set up for the assessment of the performance. Feng et al. (Feng and Joung, 2009) suggested some essential properties regarding indicators, including being measurable, relevant, meaningful, reliable, accessible and flexible. Regardless of these features, there are two approaches towards the definition and introduction of indicators and metrics: bottom-up or top-down approach. In the top-down approach, the five dimensions of sustainability are listed as leaders or headers and all possible indicators will be introduced as sub-categories. While in the bottom-up approach all possible indicators and metrics are introduced and then, assigned to the relevant dimension of sustainability. Either way, there will be indicators that would fit in two or more areas and need to be investigated carefully to reach the best possible results.

Indicators and metrics for the sustainability assessment of any desired operation can be originated and adapted from existing frameworks (GRI, UN, OECD,) or can be developed based on a deep knowledge and understanding of the operation in alliance with a standard frame or regulation.

The Global Reporting Initiative (GRI) has provided guidelines for measurement and sustainability reporting introducing 91 sustainability indicators (Rahdari and Rostamy, 2015), whilst the OECD has proposed 18 indicators for sustainable manufacturing (energy aganecy, 2018) and Eurostat has suggested just 15 sustainable indicators(Heilala et al., 2015).

Most of indicators are usually normalized and instead of presenting the total measured parameters, the measured values are calibrated in relative terms as a ratio of performance or an important concept. This will provide real insights into the concept and performance and make simple comparison with similar operations possible.

In practice, sustainability indicators provide a framework that will be used to evaluate the performance of the operation in terms of whether it is a sustainable practice or not and if it is in compliance with the global regulations. Furthermore, the generated measures, numbers and reports can be used in combination with available benchmarks and target metrics to investigate possible options in order to redesign the process and optimize the operation.In addition, reports can be used as guidelines for current and future market opportunities in terms of investment and expansion activities.Hence, sustainability assessment is not just a methodology to assess and investigate the performance of the operations, it is also about providing reliable grounds for the design, engineering and financial decision making at the production and management levels. Ultimately, the impact and quality of measurements, analyzes and results determine the success of decisions, designs and future plans.Thus, it is very important to define a meaningful list of indicators with realistic metrics that can achieve all mentioned aims as they determine how successful and achievable a process would be. This practice is vital for all machining operations, especially non-traditional micro machining methods, including μECM, which still quite nascent and with the help of a feasible sustainability framework smoother and economic development can be achieved.

Whilst the common belief would suggest that micro scale machining implies improved sustainability by reducing raw material usage, less energy consumption and less environmental impact, this may not be always the case. De Grave et al. (De Grave and Olsen, 2006) have shown that some factors can prevent achieving sustainable micro-machining . Hence, it is necessary to establish a similar framework for micro machining sustainability assessment as for macro industries.

In this work, the top-bottom approach has been used to identify and introduce relevant indicators and metrics for μECM sustainability assessment.

2.1.1. Energy consumption

In terms of energy, the assumption is that new technologies will use less and should be more productive, but in an industrial environment this is not easy to judge without enough data and measurements. Whilst there is the possibility of using less energy at the production level for micro-scale machining, it is important to consider the need for ventilation, filtering and maintaining the clean room, which would increase the cost of energy.

Electrical energy consumption: can be used as an indicator to assess the energy consumption of the μECM process. Regarding which, the current energy related indicators are time based. Also, in the machining process, machining time predominates in terms of the energy demand. Therefore time is very important variable to be considered in energy consumption assessment. However, a time-based energy indicator in the machining process assessment is not sufficient without considereing the material removal rate (MRR). Thus this indicator should be at least a two dimensional function of time and material removal rate (MRR). A high MRR without having a precise finished product, would hinder the operation. Hence, adding the precision percentage as third dimension to this function is necessary to provide useful required data.

$$Electrical\ energy\ consumption = f(time, MRR, \%precision) \tag{1}$$

The energy consumption indicator should capture the sum of used electrical energy by the μECM process and within the workshop. The general area of power consumption can be considered as a function of time and production, but the machining energy consumption should be seen as a function of three dimensions.

Table 1, summarizes the effective aspects of this indicator.

Finally, the sum of the mentioned functions can be calculated using the equation below.

$$\begin{aligned} Energy\ consumption = &\sum_{k=1}^{4} f(time, productionunit) \\ &+ \sum_{l=5}^{8} g(time, MRR, \%precision) \end{aligned} \tag{2}$$

Water consumption: μECM is based on anodic dissolution, which using aqua solutions and the electrolyte is continuously flowing while the process is taking place. The volume of the used water in the process should be measured as a function of time and MRR (f1), but there is general water usage in the factory as well, which can be measured as a function of time and production level.

$$Water\ consumption = f1(time, MRR) + f2(time, production\ unit) \quad (3)$$

If other forms of energy are consumed during the production (machining), these need to be assessed as well. Another matter to consider is the different modes of machine states: idle, standby, start up and busy. The energy consumption functions can be adapted to each different state.

Machine tools are the most dominant element in energy consumption in the machining operation (Priarone et al., 2018). Hence, one of the core concerns in research is to minimize the tools energy consumption. This will technically lead to a reduction in energy consumption and consequently positive environmental impact and reduction in the process cost.

In addition to direct energy usage, there are other measures to consider such as the percentage of used energy from renewal and green energy resources. Such indicators can be taken into account in a bigger frame for the factory performance, rather than the machining process sustainability assessment.

2.1.2. Waste management

Indicators to be used in waste assessment in the μECM process are as follows.

Material waste: Regarding which, the volume of defects should be considered. In addition to this, the μECM process usually produces very high value

Function	**Activity**	**Details**
F1	Logistics	Lighting, heating, cooling, cooking, IT
F2	PC and peripherals	PC, printers, monitoring unit
F3	Cooling unit	To maintain the electrolyte temperature
F4	Clean room	Using clean room for special activities
F5	Power supply unit	Current/Voltage pulses
F6	Control unit	Digital and analogue control unit
F7	Spindle motors	Spindle motors
F8	Spindle motors	Axis movement in three dimensions

Table 1: Effective factors in energy consumption indicator

added products for specific applications and in most cases the required materials have significant commercial value. Hence, any defect or waste can lead to significant unnecessary raw material costs(Mortazavi and Ivanov, 2017).

On the other hand, μECM process is known for burr free products with no thermal and physical effects. This indicates that there are decreased defects in the production line, which leads less waste and thus, will increase the sustainability of method if compared with other non-conventional manufacturing methods. To sum up all the positive and negative outcomes, the proposed indicator to present this quantity (material waste) should be a function of the produced defects in relation to the total production of finished products and unit material cost.

$$Material\ waste = f(defects\ per\ production, raw\ material\ consumption) \tag{4}$$

Tool wear: This is one of the critical aspects of machining. However, μECM has proven to have no or minimum tool wear as there is no direct contact between the work-piece and the tool. So, there is not any material waste due to tool electrode tear and wear. But, tool design and its preparation is a very cost effective process in any micro machining industry. By identifying the most suitable tool material and tool shape, the energy and material waste would definitely be decreased, because this will positively affect the MRR, accuracy and efficiency of the process. However, in spite of the obvious advantages of μECM in terms of tool wear compared with other machining processes, it is still necessary to introduce an indicator to assess the material waste due to tool deficiency as a function of tool material usage and tool damage rate per production unit.

$$Tool\ material\ waste = f(tool\ damage\ rate, tool\ material\ usage) \tag{5}$$

Chemical waste: μECM requires electrolytes to activate the reaction and create the current path between tool electrode and workpiece. Also, the flow of the electrolyte is the way to remove sludge and by-products from Inter Electrode Gap(IEG) . The electrolyte should continuously flow through the gap and be filtered or renewed so as to be free of sludge and by-products. Chemical waste is the rate of discarded electrolyte during the machining process. Hence, the relevant criterion should include electrolyte life time and the production rate.

$$\begin{aligned}Chemical\ waste = f(&discarded\ electrolyte,\ electrolyte\ life-time,\\ &production\ rate)\end{aligned} \tag{6}$$

Finally, the waste assessment indicator should be the sum of all above wastes, but should be a weighted algebraic sum.

$$\begin{aligned}Total\ waste = \alpha\ material\ waste + \beta\ tool\ material\ waste+\\ \gamma\ Chemical\ waste\end{aligned} \tag{7}$$

Waste assessment closely associated with the process environmental impact which shows the interrelation between sustainability dimensions. This will be discussed later in this paper.

2.1.3. Environment impact

In terms of μECM operation environment impact (EI) the concerns are relate to natural resources, raw materials, hazardous materials and chemicals, the return of discarded materials and liquids to the nature and so on. The environmental impact of μECM can be qualitatively and quantitatively assessed.

Natural resources: This indicator pertains to assessing the rate of the consumed energy per production unit from natural resources. With much more renewable energy being used in the system, in addition to improving energy efficiency, the impact on natural resources would decrease and the carbon foot print level would be lessened too. Hence, this indicator can be used in two ways to produce data for saving resources and producing less carbon.

Raw materials: This can be introduced to evaluate the rate of raw material usage per unit of the production which should include any defects as well. The type of input material plays an important role in the performance of the machining and its sustainability assessment, given some materials need more energy to be modified, are harder to extract from nature or have limited resources. μECM has provided opportunities to machine hard materials and semiconductors, which may have been too hard to be machined with conventional machining methods. This is an advantage and that would definitely have a positive impact on the sustainability of the process. However, it is important to have clear perception of the impact of these materials on the environment conditions.

Another important criterion is how successful is the recycling of the defects and unwanted finished products and how long needed for this to take place. Also, the cost of recycling process should be taken into account. This is problematic, for whilst μECM may not generate a lot of defects, the process of recycling may be too intricate. The less the recycle rate and the longer the return period to the nature is, the more negative the impact on the environment will be.

$$EI\ material\ waste = f(Recycling\ rate, return\ period, production\ unit) \tag{8}$$

CO2 emissions: This is very critical indicator, with various standards having been published regarding the acceptable levels for CO2 emissions for different industries. Recently, it has been reported that global energy-related CO2 emissions grew by 1.4% in 2017, an increase of 460 million tons, thereby reaching a historic high of 32.5 giga tons. However, in a few countries, including the United Kingdom, the level of emission declined. In the UK, due to the shift from coal to gas and renewable energy, a drop of 3.8% (15 million tons) in emissions observed(energy aganecy, 2018).

Chemical pollution: the impact of chemical substances and generated gases can be crucial and should be addressed thoroughly when the performance of μECM is assessed. In terms of chemical impact, it is clear that μECM requires electrolytes to activate the process and create the current path between the tool electrode and workpiece. According to Bhattacharyya, two main categories of electrolytes are being used in μECM: Passive electrolytes, which contain oxidizing anions and they are known for better machining precision and Non-passive electrolytes, which contain aggressive anions and have less effect on the electrode due to the formation of soluble products, as they can be completely swept from the IEG area (Bhattacharyya et al., 2005)

However, μECM electrolytes considered to be nontoxic. This is an advantage in measuring the sustainability of μECM with regard to environment impact but one should consider that the performance of machining would be affected by remaining sludge from removed materials during pulse on time if the sludge accumulated in the gap due to generating sparks. Therefore, it is very important to assure that any sludge and gases will be flushed away from IEG and also electrolyte will be continuously filtered or renewed.

A useful indicator suitable for assessing the environmental impact of chemical waste should present its level of hazard in relation to the unit of production and precision percentage. Hence, whilst the same indicator as chemical waste can be used to assess the environmental impact of the electrolyte waste in nature, the toxic level should also be added to the function.

$$\begin{aligned} EI\ chemical\ waste = f(&discarded\ electrolyte, toxic\ level,\\ &electrolyte\ life\ cycle, production\ rate) \end{aligned} \tag{9}$$

In addition to the above indicators, environmental standards are a useful guide towards investigation and improvement of machining performance in terms of environmental impact. ISO standards need to be followed when relevant to the nature of the operation.

2.1.4. Health and Safety

Health and safety of the operators in any work place is a very important consideration and it is the primary responsibility of the employer to provide it. There is a range of standards and regulations regarding health and safety requirements of the work floor. In the manufacturing environment, there are various health threatening and hazardous areas that need to be investigated properly and the necessary steps introduced. Vibration level, noise level, chemical gases, liquid and solid scatters, are examples of what may be a danger to the health and safety of workers.

Topics, such as exposure to toxic chemicals, high voltage energy as well as solid and chemical scatters, can be investigated as safety indicators, whilst levels of chemical contamination, noise and vibration are related to health indicators.

General speaking, there are standards out there to be followed by employers to minimize the hazard and dangers in workplace. However it is important to know what risks and hazards μECM operation can have for workers health and safety and whether the operation can meet the standards required.

There are other areas of personnel health that formally should be considered when health and safety is the concern, including staff well-being and work satisfaction, but their relevant their relevant indicators could be defined as part of the general assessment for the firm or factory.

2.1.5. Cost management

The total cost of the process is a salient matter in any manufacturing process. It is very important not only from a sustainability dimension per-

Function	**Indication**	**Variables**
F1	Noise level	Noise level, working hours
F2	Vibration level	Vibration level, working hours
F3	Electromagnet waves	Wave exposure level, working hours
F4	Toxic chemical	Volume, toxic level, exposure period
F5	High power risk	Risk probability, working hours
F6	Solid scatters	Volume, tool rotation speed, dimension of scatter, working hours
F7	Chemical scatters	Volume, dimension of scatter, tool rotation speed, electrolyte flow velocity, working hours

Table 2: Health & Safety indicators in μECM operation

spective, but the fact that the process needs to be financially attractive for the organization/investors. There is no doubt that, currently, μECM is an expensive machining method, but it has potential to be commercialized through further research. μECM machining as with any other manufacturing process requires various types of expenditure, such as the cost of operation, maintenance and labor.

The cost of operation is a relative parameter and not an absolute value. The higher level of cost does not necessary mean a too expensive operation, for it may make the whole process more effective through improving the quality of products and increasing the efficiency of the system.

In a way cost of the machining process is under the effect of all other sustainability dimensions, so development of any cost indicators is developing of indicators with interrelationship. The cost indicator should include the following areas.

Cost of labor: this indicator will pertains to assessing any labor expenses, which will include, rates of pay, working hours and number of workers involved in the work flow. In addition , this indicator would present any extra action been taken place in order to provide a better work environment for the workers, especially in terms of the employeeswell-being and work satisfaction.

Cost of energy consumption: This indicator refers to a different approach to considering energy efficiency in the process. The most important parameter is the source of the energy, where renewable and green energy would cost less than using coal and electricity. Regardless the source of the energy, the cost of consumed energy can be divided into two main categories, as follows:

There is a general cost of energy, which covers heating, cooling, cooking and lighting of the workshop or factory etc.

Then, there is the cost of energy consumed by machinery equipment, such as spindle motors, DC axis motors, machine pump as well as, control and power supply unit. This category needs detailed analysis as the expenses vary according to the machining quality and machine setup. Hence, in this assessment the quality of final product and precision percentage should be considered. So, this indicator is a relative variable depending on the quality of final product and clearly, improved quality comes with a price.

Cost of maintenance: maintenance fee includes any repair and expenses to maintain the production of the machine. It is a sum of expenses which paid for regular inspection, breakdown recovery, part exchange and regular cleaning. The maintenance cost will be a function of working hours of the machine.

Cost of consumables: this includes materials, electrolytes, tool materials and preparation. The cost of tool preparation is quite high, but assessment of this cost in terms of the production unit will make it efficient as there is no tool wear in the μECM process.This indicator, in a way presents the cost of intermediate parts which involve a high share of the process resources and activities.

Cost of by-products disposal: this should be done according the standards. By-products of the μECM operation are in the form of combined sludge, chemical liquid, which has a strict disposal process to follow and should be actioned by trained workers. The cost needs to be considered per unit of production.

All other costs: Any other expenses that do not fit in the above categories, but are necessary for running the operation and production line should be taken into account as well.

As the above descriptions and explanations present, cost management can be considered as an overseen factor in sustainability, which directly or indirectly would use all other indicators and metrics to assess the cost of the process. This criterion is a great help when it is the time to restructure the process and reinvest in order to improve or expand the work.

Whilst the relation between the cost dimension and all other dimensions of sustainability is very clear, does not make the assessment straightforward as the price can change with a slight shift in the operation, quality and precision of the process. Similar relations are observed among all other dimensions as well: improved impact on the environment comes from energy consumption

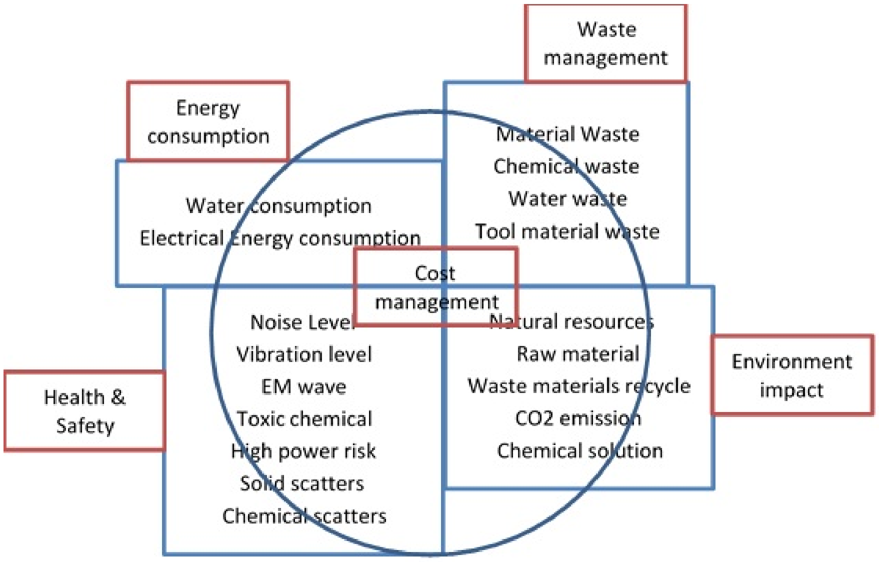

Figure 3: Brief presentation of μECM sustainability indicators and their dependency

efficiency, lower material usage stems from fewer defects, improved health and safety comes from improved chemical disposal and so on.

As figure 3 shows, there is not any solid boundary between the five dimensions of sustainability, but rather, there is a shared space between them, which symbolically presents their interrelation. Understanding this complex interrelation is crucial and should be investigated carefully as will substantially affect the outcomes.

3. Discussion

μECM method is an expensive technology and needs a higher initial investment in comparison with other non-conventional micro machining methods.This feature from one side, and the complex nature of the μECM from the other side, are the key reasons why it has not been able to attract enough interest to be commercialized and be used widely in the industrial environment.Hence, Creating a frame work for the evaluation and investigation of the sustainability of μECM will help to expand it and perhaps make it more interesting for investors.

For special types of material, including hard materials to machine, fragile ones and superconductors, μECM could be the only method which can provide maximum accuracy and minimum damage. There are other materials that could be machined using μECM and other alternative methods. Sustainability measures can help to identify the most optimum methods for machining this group of materials. And of course, sustainability measurement can prevent the waste of resources, if μECM is not the best method to be used.

Table 3 has summarizes the introduced metrics in the dimensional sustainability assessment for the μECM process. Whilst these cover all dimensions of the sustainability assessment but this is not enough, for in addition to the results and acquired data, their accurate interpretation is just as important as obtaining the data through the indicators in the first place. That is,as the μECM process is a multidisciplinary process and a slight change in machining parameters can change the result significantly, clearly understanding how these metrics work is crucial. In addition to the machining parameters, precision and accuracy of the final product will affect the interpretation of the metrics and indicators. Also, should not be forgotten that the interrelation between metrics and indicators can change the sustainability assessment results substantially. Therefore, it is very important to be alert to these matters and be able to respond appropriately when necessary.

A brief review on table 3 and figure 3 confirms that the interrelation between the dimensions of the sustainability exist almost between all metrics. In addition, most of these metrics have dependency on the unit of production, quality of the finished work and its precision percentage.

Although, the above proposed approach for the sustainability assessment of the μECM is the unique approach in this field and thus there is not any other approach to be analytically compared with, but there are examples of recent researches in the field of machining sustainability assessment which can help to present the possible advantages of the proposed work for the future.

Mia et al(Mia et al., 2018) investigated the machining performance of hardened AISI1060 steel under different cooling lubrication conditions and presented the results in terms of cutting temperature and surface roughness, and finally used the Pugh matrix environmental approach to assess the sustainability of the process among studied conditions.

The similarity between above mentioned example and proposed approach is that the machining outcome can differ based on initial machining set up; therefore, the aim is to find the optimum machining outcomes and assess the sustainability of the optimized approach.

Dimensions	**Metrics**
Energy consumption	Water consumption
	Machine usage of power electricity
	Operation usage power electricity
	Any other energy usage
Waste management	Material
	Energy
	Gaseous waste
	Chemical
	Hazardous
	Liquid waste
	Water waste
Environment impact	Polluted Water release
	Renewal energy usage
	Chemical disposal rate
	liquid waste disposal
	CO2 emission
Health & safety	Liquid scatter
	Material (solid) scatter
	Exposure to toxic
	Exposure to high temperature
	Exposure to high voltage
	Noise level
	Vibration level
	Other hazardous exposure
Cost management	Raw Material Cost
	Water recycle cost
	Power electricity cost
	By-products treatment cost
	Labor cost
	Operation cost
	Water cost
	Other hazardous exposure
	All other expenses

Table 3: μECM sustainability metrics and indicators

One of the features of the μECM technology is the high share of intermediate parts (stages) which can not be seen at the final product but are very significant towards the performance of the process.

By introducing various indicators for all dimensions of sustainability, it has been tried to cover all these intermediate parts and stages to have a more accurate picture of the process sustainability, specially knowing that these intermediate parts have impact on all five sustainability dimensions. Therefore, in addition to considering the dependency of the assessment to the process output features (like machining accuracy and MRR), the effect of intermediate parts and stages have been considered, too.

The second difference and in fact one of the aims of the proposed approach is to be able to find optimized machining parameters not only for better machining output but to have a more sustainable approach. Therefore, the risk of optimization with sacrificing the nature, environment or energy resources will be limited and a balance between optimized machining set up and sustainable performance would be achieved.

μECM is a complicated and multidisciplinary method based on a mysterious electrochemical phenomena which yet to be fully investigated; machining parameters are in a very complex correlation and any change in one parameter can affect the whole process and the machining outcomes.

As an example, Ikkala et al(Ikkala et al., 2015) showed that by increasing MRR, machine tool energy efficiency can be improved. This can be achieved by changing the machining parameters, including the pulse supply features, electrolyte type and features, feed rate, tool rotational speed and the IEG size.Hence, energy efficiency depends on all these parameters. In addition to this, the quality of the final product can be improved by changing any of these parameters. However, the combination of these parameters may have different impact.

Increasing energy efficiency by sacrificing the quality is not a sustainable approach and wise decision to take; finding the balance between process efficiency and quality of the finished product is a challenge yet to overcome.Having a set of accurate, detailed and reliable machining parameters for μECM would improve sustainability assessment of the process. Furthermore, this can lead to the creation of a comprehensive set up that can help in delivering a productive economic method for desired machining.

And finally, the hope is that by presenting advantages and potential of the μECM process in terms of the technology ,environment friendly and operator safety, be able to justify its initial high cost and promote it to the industrial level.

Next section presents two examples of the application of the μECM technology.Also, figure 4 illustrates the proposed assessment flow chart.

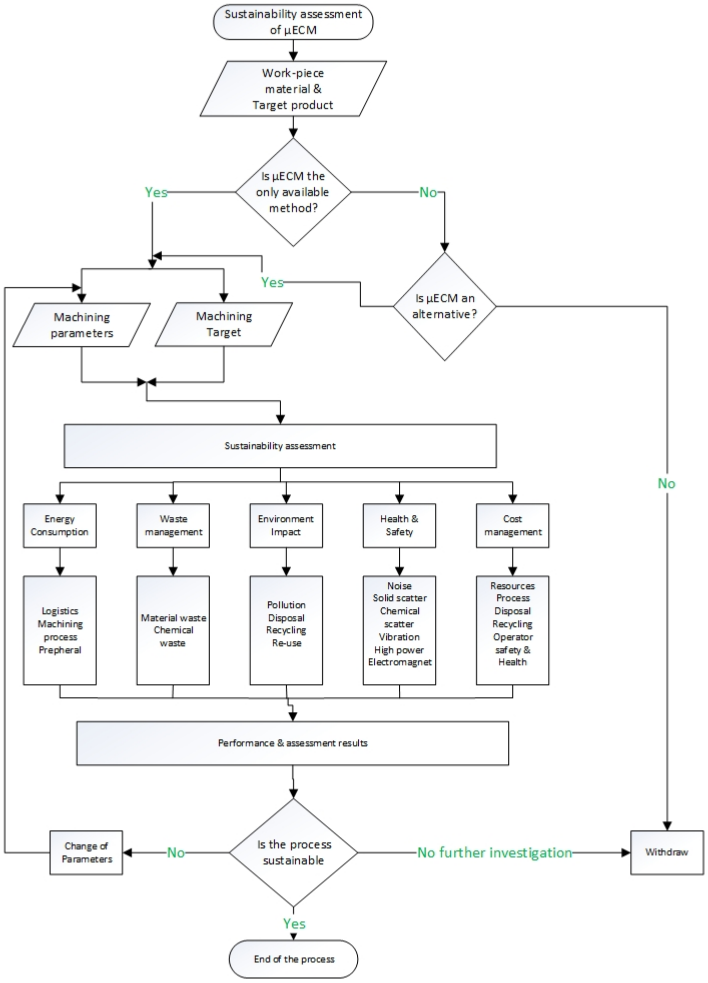

Figure 4: μECM sustainability assessment flow chart

4. Case studies

In this section, couple of examples of machining processes using μECM are discussed. As mentioned earlier, this process is an alternative in machining, which has not been expanded to the commercial environment, as yet.

Hence, the application of all above metrics and indicators was not possible at this stage and for these case studies. There is an important first step to start assessing the sustainability of the μECM process with; the question is as whether there is an alternative to using this method. The answer could be no when the materials are fragile and superconductive, as currently there is no other option than using μECM. In such cases, sustainability assessment can be aimed at improving the process and finding optimal machining parameters.

While there are alternatives for the machining process, sustainability assessment is a great approach to find the best possible options, if assessment results are comparable.

- Case study 1: Shaping InSb Single Crystal wafer for space application

  Semiconductor wafers are diced into smaller pieces in order to be used as substrates for chips. The process of dicing creates a defective layer onto the machined surfaces. Later the diced pieces are etched in order to remove this defective layer. Dicing is again limited to the shape of the chips which can be created from the wafers and in most of the cases its shape is just a rectangle. Dicing is also not applicable if the wafer is very brittle and when diced the wafer breaks in small pieces.

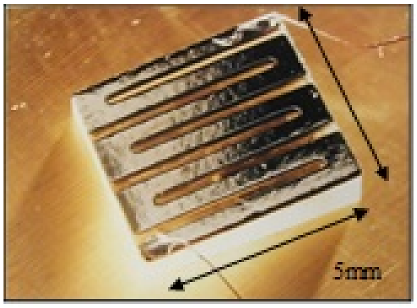

Figure 5: Evolution of sensor shape achieving better product characteristics after using μECM process

  μECM technology can be applied instead of dicing in order to avoid the creation of the defective layer and the following etching process; also the process would not be limited to the shape of the chip to be cut or to the brittleness of the wafer as μECM technology is a non-contact technology. QMC Ltd requested test cuts for Indium antimonite (InSb) which to be used as a basis for sensing very low temperatures in cryogenic installations or in space applications. This is extremely brittle material and any other machining method cannot produce the required samples. It was attempted dicing and EDM machining but both processes failed. As investigation and researched showed, NaCl and NaNO3 could activate the anodic dissolution of InSb. The proposed technology for manufacturing of complex shaped semiconductor materials shown on Figure 4 without creation of defective layer and safeguarding the properties of the basic material is the only method available at present (Mortazavi and Ivanov, 2016).This practice, presents the advantage of μECM by improving final product without using toxic solution. μECM process also allowed the shape of the part to be changed in order to avoid sharp corners and finally the sensor produced from this sample to have better characteristics.

- Case study 2: Sharpening medical needles using μECM technology

Traditionally medical needles are produced from stainless steel tubing and process used for sharpening is grinding. The temperature in the contact point of the grinding wheel and the stainless steel tubing is 600-700 degC. When the wheel goes to the tip of the needle, the heat is trapped and the tip very often is bent and burned. The sides of the needle are with jagged edges. All these causes pain when the needle is inserted. On another hand grinding process for sharpening can produce only flat surfaces, so all sharpening is done by introducing flat surfaces onto the stainless steel tubing. In this case the biophysical needs for the use of the needle is not taken into account. BROUN GmBH (needle manufacturer from Germany) approached the research team requesting to test μECM technology for sharpening medical needles. The main advantages are that the machining time per needle without any optimization was 10 sec. Actually for 10 sec can be produced hundreds of needles if appropriate jigs and fixtures are used. Another benefit was that sharpening of the needle can be done 3D shaped and the need for introducing a medication or taking sample liquid out also can be used to shape the needle appropriately. Final result was that there were no jagged edges and the needle can be sharpened down to few micrometers on the very tip. This depends on the grain structure of the stainless steel tubing. The advantages of the μECM sharpened needle are obvious including smoother surfaces, sharped tip and therefore less

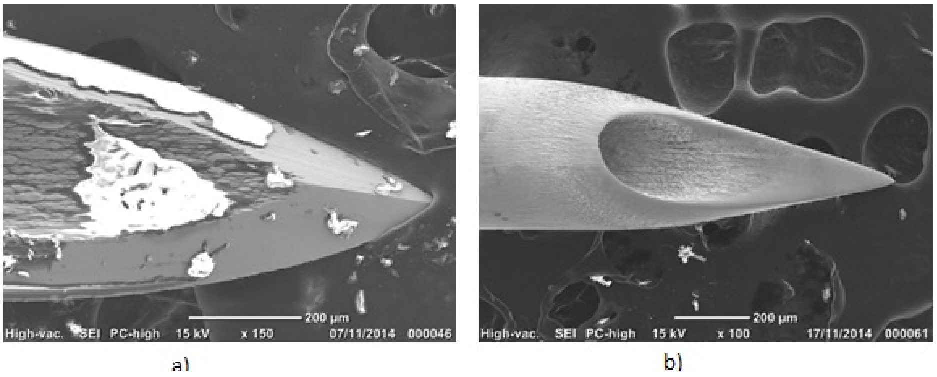

Figure 6: a)Ground needle tip, b)μECM machined needle tip

pain (Figure 5). Larger opening and smoother inside surface which will allow better introducing the medicine and not allowing the tissue to grow onto the rough internal surface if the needle is used for long time.(Mortazavi and Ivanov, 2016). This practice, presents the advantage of μECM by improving final product features and minimizing machining time.

5. Conclusion

Sustainability assessments and sustainable development is an issue that likely to increase in importance exponentially in the near future. Currently, assessment for sustainable systems and processes is widely neglected, with most efforts being concentrated on the product level and supply chain. In addition to this, in the micro manufacturing field, non-traditional micro manufacturing methods have received less attention compared with conventional methods in spite of increasing demand to be used in the industry. In this work, the aim has been to promote the importance of the sustainability evaluation of μECM as a non-traditional micro machining process in recognition of μECM as of it being the best option for machining special types of the materials including but not limited to hard materials to cut, conductors and superconductors.

Improving sustainability assessment of μECM process and refining the interpretation of the assessment results can help to create a new ground to investigate optimized machining parameters to achieve higher accuracy and precision within a sustainable frame.

As aforementioned, in spite of the valuable advantages of μECM over other machining processes, this technology is still at the research level and has a long way to go until it becomes a commercial technology. The main reasons behind this are the expensive structure, uncertain and complex nature of the electrochemical process and process dependency on the operator experience. Hence, there is still a huge gap between practices at the research and commercial levels. However, sustainability assessment may help in addressing this by proving the process value and profitability in spite of its high investment cost.

Currently and based on μECM process features and introduced assessment approach, the assessment results should be interpreted based on general guidelines and manufacturer expectations but by implementing this process and gathering more date it is possible to prepare a benchmarks for all measures and indicators and be able to generalize the results and make them comparable.

The suggestion for the future work is to advance the research by developing an assessment model based on artificial intelligence or neural networks using the above indicators and metrics in order to have a uniform investigation method for any material and product. Any further development would still face the challenge to promote the μECM at industrial level and be able to apply all above criteria and measures in real life of the process.

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