SUSTAINABILITY ASSESSMENT OF MACHINING PROCESSES

by

Syed Waqar Raza

A Thesis Presented to the Faculty of the
American University of Sharjah
College of Engineering
in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Mechanical Engineering

Sharjah, United Arab Emirates

December 2013

Approval Signatures

We, the undersigned, approve the Master's Thesis of Syed Waqar Raza.

Thesis Title: Sustainability Assessment of Machining Processes

Signature	**Date of Signature** (dd/mm/yyyy)
___________________________ Dr. Ibrahim Mostafa Deiab Associate Professor Department of Mechanical Engineering Thesis Advisor	_______________
___________________________ Dr. Basil Mohammad Darras Assistant Professor Department of Mechanical Engineering Thesis Committee Member	_______________
___________________________ Dr. Hazim Sayed El-Baz Associate Professor Department of Industrial Engineering & ESM Thesis Committee Member	_______________
___________________________ Dr. Andreas Poullikkas Visiting Associate Professor Department of Mechanical Engineering Thesis Committee Member	_______________
___________________________ Dr. Ibrahim Mostafa Deiab Head, Department of Mechanical Engineering	_______________
___________________________ Dr. Hany El Kadi Associate Dean, College of Engineering	_______________
___________________________ Dr. Leland Blank Dean, College of Engineering	_______________
___________________________ Dr. Khaled Assaleh Director of Graduate Studies	_______________

Acknowledgements

I would like to express my heartfelt gratitude to my advisor Dr. Ibrahim Deiab, for without his insight and guidance (both technical and non-technical) this work would not have been completed. A true mentor, he remains a figure of inspiration and I feel fortunate to have come across him. I would also humbly thank Dr. Basil Darras, Dr. Hazim El-Baz and Dr. Andreas Poullikkas for taking out time to review and improve this work with their valuable insights and providing their kind guidance.

From the Manufacturing Laboratory at AUS, I would like to offer special thanks to Engr. Salman Pervaiz, for he was always welcoming and available to assist and guide me during this project. I also feel indebted to Mr. Ricardo de Jesus, who was able to work tirelessly with me throughout the experimental work and provided valuable opinions from time to time. Moreover, I would like to thank Engr. Baraa Jamal Emran, Engr. Muhammad Taha and all those who have, in any way, been instrumental in completion of this work. The support provided by Mr. Milan Martinovic and Accu Svenska AB also needs a grateful mention. Lastly and most importantly, I gratefully acknowledge the help and support provided by the National Research Foundation (NRF) U.A.E. Their kind patronage was chiefly instrumental in seeing this project through to the end.

Dedication

In the name of Almighty Allah, the source and origin of all knowledge of present and otherwise, I dedicate this effort of mine to

My father, who in his life and death, is a constant source of strength

My mother, whose constant prayer is my guardian angel

My loving sister and brother

Abstract

There is an increased interest in sustainability assessment of manufacturing systems and processes. Various machining practices are being proposed as sustainable and require careful investigation. The current sustainability assessment models (e.g., Life Cycle Analysis [LCA]) present a holistic approach without much focus on process specific details. This project presents a more flexible '*XSI*' approach for defining sustainability indices where X can be a sustainability perspective (e.g., Energy Sustainability Index, ESI). These sustainability metrics can comprehensively quantify machining processes in terms of impact on the environment and power consumption in a flexible manner. In addition, introducing the concept of normalization with respect to the '*feature-of-interest*' enables a flexible rating system in terms of process types and perspectives. A user-friendly calculator is developed, which converts a set of input machining parameters into a set of measurable rating quantities and indices including but not limited to production rate, production cost, tool life/cost, energy consumption and environmental burden. This will enable the manufacturing engineer to make an informed decision about parameter selection and process design for sustainability. Machinability of titanium alloy Ti-6Al-4v is used to validate and improve the proposed approach and assess proposed practices like hybrid machining and vegetable oil lubrication.

Search Terms: Sustainability, Sustainability indices, LCA, Ti-alloy, Machining

Table of Contents

List of Figures

List of Tables

Nomenclature

ANN	Artificial Neural Network
ANOVA	Analysis Of Variance
CSI	Coolant Sustainability Index
d	Depth of Cut
DoE	Design of Experiments
EPD	Environmental Product Declaration
ESI	Energy Sustainability Index
$E_{consumed}$	Sum of dry run energy and Cutting Energy
E_{cut}	Cutting Energy estimated using Power Factor
$E_{dry\ run}$	Energy consumed in dry run with no depth of cut
f_m	Cutting Feed Rate
f_R	Cutting Feed
FSI	Financial Sustainability Index
HVAC	Heat Ventilation & Air Conditioning
L	Length of Cut
LCA	Life Cycle Assessment
LN2	Liquid Nitrogen
MQL	Minimum Quantity Lubrication
MQCL	Minimum Quantity Cooled Lubrication
MRR	Material Removal Rate
OECD	Organization for Economic Cooperation and Development
PSI	Product Sustainability Index
T_m	Machining Time
V	Cutting Speed

1. Introduction

1.1 Preamble

The manufacturing sector of today needs a comprehensive sustainability assessment methodology. Usually LCA methodology can perform this task but for that it is important that the manufacturing phase of the product or the use phase of the machine tool is focused upon first. There is a need for sustainability metrics that can comprehensively describe the machining process. This work aims to select a set of sustainability metrics and then use these metrics to build a simulation tool, a sustainability calculator, to investigate the sustainability of machining processes by developing such metrics and a calculator that utilizes these metrics/indicators. The calculator will assess various machining scenarios based on a set of proposed sustainability indicators. The concept of normalization with respect to the desired feature is applied in this regard. The calculator should be able to convert a set of input machining parameters into a set of measurable rating quantities including but not limited to production rate, production cost, tool life/cost, energy consumption and environmental burden. This will enable the manufacturing engineer to make an informed decision about the optimum manufacturing scenario. A set of cutting tests were performed in the lab to collect real data for different case studies that were used to validate and assess the feasibility of the calculator.

The objectives are of this study are:

- Review open literature, select and develop set of elaborate, extensive and generic sustainability metrics which are easy to use, comprehend and evaluate regardless of the specifications of the processes and thus fill an existing void of suitable sustainability indicators.
- Establish a methodology for evaluating sustainability of machining processes.
- Develop a reliable, user-friendly and interactive calculator for evaluating sustainability of a given machining scenario.
- Evaluate certain scenarios using the proposed metrics and developed calculator.

1.2 Literature Review

The scope of this thesis is two-fold. The first objective is to support research in the field of sustainability assessment of machining processes and the second is to analyze the so-called ‘sustainable’ practices in machining. The former thus requires a survey of the work that has previously been done in order to rate sustainability. The latter covers various lubrication methodologies that are proposed as sustainable alternatives to conventional practices. Hence the literature review has been accordingly divided into two sections.

1.2.1 Sustainability Measurement

The concept of sustainable manufacturing has been a key area of research in recent times. Many efforts have been made to incorporate sustainability into manufacturing systems so that environmental, economic and societal constraints can all be satisfied. The U.S. Department of Commerce defines sustainable manufacturing as “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [1]. To rate a system or to measure the improvement in an existing system in terms of sustainability is potentially very difficult [2]. This calls for a set of limited metrics based on standardized measurements that help decision making at all levels [2],[3]. Metrics ‘enable technology’ in design processes and even if they are subjective and variable, they are still important for informed decision making [2],[4]. Various studies have been carried out in different manufacturing sectors but the machining sector still needs more in this regard. Machining processes are very important manufacturing processes that lie at the core of almost every industry [5]. The advent of sustainability principles has also lead to research in the field of machining processes.

Mani *et al.* [6] argued that the global trend towards sustainable manufacturing practices calls for sustainability criteria to be developed. They show that the current manufacturing indices of cost, time and quality need to be complemented by sustainability. For this purpose they propose the idea of ‘Energy Monitoring’. They justify this proposition by first establishing the importance of energy in manufacturing. . It is shown that almost 21.6 percent of the total energy consumption in the US is covered by the industrial sector and out of this, 70 percent can be attributed to manufacturing processes. Also, 5 percent of the US GDP is from the manufacturing sector. Energy enables manufacturing operations that add value to intermediate products as they are progressively transformed into final consumer goods. It is explained that the activities that provide energy efficiency also provide better control over plant assets and inputs. Thus energy efficiency is not only important from an environmental perspective but is also significant in terms of achieving corporate goals through better productivity. After sufficient study and research, energy monitoring for sustainability through an energy consumption index will minimize energy use and improve productivity through improved engineering of product and process. It will also promote a business that is both environmentally and economically competitive. Companies will be able to implement a comprehensive monitoring and preventive maintenance program that considers energy usage by factoring energy consumption into any plans that include asset acquisition, allocation, or replacement. The use of ISO 14000 series is proposed as well, so as to assist the execution of life cycle analysis (LCA).

Pusavec *et al.* [7] stressed the importance of incorporating sustainability in manufacturing processes and especially machining processes. The landmarks of a sustainable process are identified as machining costs, environmental friendliness, energy consumption, waste management, personnel health and operational safety. Building on these concepts the study proposes the idea of cryogenic machining. However, more importantly, the study includes a comparison of two machining processes in a very effective tabular representation that involves the necessary input parameters of the machining process, the time and energy consumed and the cost at different stages to give an overall cost comparison. This comparison can help in developing a sustainability calculator by taking in input parameters and evaluating a process.

A special report was prepared by General Motors in collaboration with research groups [8]. This report proposes set of metrics for measuring sustainability in General

Motors from various perspectives. These perspectives involve six major categories: costs, environmental friendliness, energy consumption, waste management, personnel health and operational safety. These are further subdivided into other metrics, some of which are of interest.

The report contains useful guidelines for metric characteristics:

- “Address the needs of all stakeholders (community, government, and business)
- Facilitate innovation and growth; continuous improvement must be the cornerstone
- Harmonize local, state, national, and international levels of business units and operations
- Be fully compatible with existing business systems (add value)
- Measure the right things – what is measured is what gets managed”

The importance of using the 6Rs (reduce, remove, recycle, recover, redesign, remanufacture) approach was discussed in the same study and based on the nature of a production plant, metrics were suggested. Since the study at hand is more specific and deals with performance in machining processes, the areas of interest are cost, environmental friendliness and energy consumption. Regarding these areas, the key indicators can be the annual energy consumption, rate of recycling, CO_2 footprint and the cost of material, process, etc. The study also discusses a number of relevant existing standards that may help in the selection or development of metrics, along with the best practices of peer industries while elaborating on the importance of adopting sustainable practices in the modern era of manufacturing.

Diaz *et al.* [9] established the importance of energy consumption of machine tools and discussed that the importance of the energy consumption in the manufacturing phase is also important, something not done in previous work that focuses only on the use phase. The study analyzed the lifetime energy consumption of a machine tool by taking into account the effect of the manufacturing environment, transportation, cutting fluid, HVAC, lighting, and automation. The results of this analysis are largely discussed in terms of energy optimization and percentage CO_2 reduction. The authors believe that the analysis can be extended to other manufacturing processes apart from machining, and provides greater clarity on the manufacturing phase as the purpose of a machine tool is to manufacture other products. The results include a discussion on the energy consumed during the life cycle of the machine tool and two certain milling machine tools are studied and compared for that purpose. The manufacturing phase, transportation, use phase and end of life are taken as the relevant life stages. Three different scenarios of a job shop, community shop and commercial shop are studied as the varying manufacturing environments and the impact of the manufacturing phase and the previously untouched side of the use phase like HVAC, lighting, and automation etc. are discussed.

Feng *et al.* [10] argued that the measurement of sustainability in manufacturing is an enabler to quantitatively measure performance in sustainability in specific manufacturing processes. A sustainable manufacturing measurement infrastructure was proposed in the study. The components include sustainable indicators and metrics repository, measurement methods, guidelines, and sustainability performance analysis and report. A very comprehensive list of available systems of rating sustainability and the standards that are serving the purpose for now along with their sources is presented in Table 1.

A general outline of the characteristics of the metrics given from ISO 14031 standards is presented in [10], stressing that they should be

- Measurable: Indicator must be capable of being measured quantitatively or qualitatively in various perspectives.
- Relevant: Indicator must show useful meaning on the manufacturing processes under evaluation.
- Understandable: Indicator should be easy to understand.
- Reliable/Usable: Reliable measurement is necessary.
- Data accessible: Indicator has to be based on accessible data.

- Flexible: An indicator must be compatible with open standard expressions for future use.

Table 1 List of Indicators

Indicator Set	components	Reference
Global Report Initiative (GRI)	70 indicators	http://www.globalreporting.org/ReportingFramework/ReportingFrameworkDownloads/
Dow Jones Sustainability Index (DJSI)	12 criteria based single indicators	http://www.sustainability-index.com/07_htmle/publications/guidebooks.html
2005 Environmental Sustainability Indicators	76 building blocks	http://www.yale.edu/esi/ESI2005.pdf
2006 Environment Performance Indicators	19 Indicators	http://sedac.ciesin.columbia.edu/es/epi/downloads/2006EPI_Report_Full.pdf
United Nations Committee on Sustainable Development Indicators	50 indicators	http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf
OECD Core indicators	46 indicators	http://www.oecdbookshop.org/oecd/display.asp?sf1=identifiers&st1=972000111E1
Indicator database	409 indicators	http://www.Sustainablemeasures.com
Ford Product Sustainability Index	8 indicators	http://www.ford.com/doc/sr07-ford-psi.pdf
GM Metrics for Sustainable Manufacturing	46 Metrics	http://actionlearning.mit.edu/s-lab/files/slab_files/Projects/2009/GM,%20report.pdf
ISO 14031 environmental performance evaluation	155 example indicators	http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_ics_browse.htm?ICS1=13&ICS2=20&ICS3=10
Wal-Mart Sustainability Product Index	15 questions	http://walmartstores.com/download/3863.pdf
Environmental Indicators for European Union	60 indicators	http://biogov.cpdr.ucl.ac.be/communication/papers/tepi99rp_EN105.pdf
Eco-Indicators 1999	3 main factors based single indicator	http://www.pre.nl/eco-indicator99/ei99-reports.htm

A discussion of using the presented methods of sustainability measurement was presented with a proposed infrastructure of methodologies and standards. After this a sample case-study was presented in the perspective of CO_2 emissions. The process sustainability indices are selected to be the weight of CO_2 produced and the energy consumed during the process of machining.

Jayal *et al.* [11] discussed the issue of sustainability and its measurement in the perspective of relevant levels. At the product level there is a need to move beyond the traditional 3R concept promoting green technologies (reduce, reuse, recycle) to a more recent 6R concept forming the basis for sustainable manufacturing (reduce, reuse, recover, redesign, remanufacture, recycle), since this allows for transforming from an open-loop, single life-cycle paradigm to a theoretically closed-loop, multiple life-cycle paradigm. At the process level there is a need to achieve optimized technological improvements and process planning for reducing energy and resource consumptions, toxic wastes, occupational hazards, etc., and for improving product life by manipulating process-induced surface integrity. At the system level there is a need to consider all aspects of the entire supply chain, taking into account all the major life-cycle stages – pre-manufacturing, manufacturing, use and post-use – over multiple life-cycles.

In addition to this, a quantification method for rating sustainability is proposed by suggesting Life Cycle Assessment (LCA) under the banner of a Product Sustainability Index (PSI). Although no rating scale is defined for any kind of process, useful areas of focus are suggested. At the end it was concluded that achieving overall sustainability requires a holistic view spanning the entire supply chain, including manufacturing systems and processes, and involving multiple product life cycles, and this requires improved product performance models, predictive process models and optimization of individual manufacturing processes, as well as optimization of the entire closed-loop supply chain operations.

Schmidt *et al.* [12] explained the use of the Product Safety Index (PSI) at the Ford Motor Company. The development of this system of sustainability management and rating was developed under the guidelines provided by ISO 14040 in terms LCA methodology. The set of relevant metrics includes eight indicators which belong to three generic categories: environmental, social and economic. These indicators are Life Cycle Global Warming Potential, Life Cycle Air Quality Potential, Sustainable Materials, Restricted Substances, Drive-by-Exterior-Noise, Mobility Capability, Safety, and Life Cycle cost of ownership. Owing their existence to a car manufacturing company, most of the indicators are specifically related to the product itself. It is also stated that the “PSI is not reduced to a single score as sustainability is by definition not one-dimensional but always measured by different indicators.” For manufacturing operations in particular, a manufacturing sustainability index (MSI) which is built on the same principles is proposed. Thus, improvements using PSI comparisons show that this can serve as a useful tool.

Narita *et al.* [13] proposed the use of environmental burden analysis of a machining operation to evaluate the process using the LCA approach. An environmental burden analyzer was developed that breaks down machining processes into various components and then calculates the environmental burden for each. To calculate the environmental burden, the idea of using the relevant emission intensities is utilized. These intensities are given in terms of kilograms of CO_2 per unit of resource consumption. It is also argued that the most significant and dominant of all gases in terms of environmental burden is CO_2. It can be seen that the environmental burden is a very useful indicator for sustainability evaluation. Also, the idea of using emission intensities is useful for evaluating energy consumption, coolant usage, etc. Thus the study provided very useful input for developing a sustainability calculator.

Rajemi *et al.* [14] developed a model for optimizing the energy footprint for a machined product. First of all, the total energy of machining a component by the turning process for a specific material in dry cutting conditions was modeled and optimized to derive an optimized tool-life that satisfies the minimum cost requirements and then the one with the lowest energy footprint requirement. The optimization criterion was extended in terms of minimum energy into two cases with one of them accounting for embodied energy for tools. Three levels of cutting velocities were used to find the velocity exponent. Then for one minimum cost and two minimum energy cases the tool life was optimized. Additionally, the problem regarding the effect of system boundaries in determining optimum machining conditions and the conflict between economical and sustainability requirements is explored.

Pusavec *et al.* [15] argued that to tackle the modern-day challenges regarding the issue of sustainability, a sustainable development trend has to be synergistically induced in a setup at all levels, which includes machining processes. It is advocated to use of cryogenic machining with experimental results through the analysis of cutting forces, tool-wear, temperatures and costs. The study proves that cryogenic machining technology has a high potential to cut costs and improve competitiveness by reducing resource consumption, creating less waste, and having less of an environmental and social impact. The results show that, even though the initial cost and effort involved with cryogenic machining are higher, it can obviously offer significant sustainability benefits. They may come through shorter production cycles and the lower cost needed to machine a part as well as the enhanced productivity due to higher output.

Pusavec *et al.* [16] stated that the idea of sustainable development is well defined and implemented on the production macro level, but there is a severe lack of implementation practices on the shop floor dealing with machining technologies. The industry is striving to achieve sustainability through changes in product, material cycles, the recovery of resources, and innovations in production practices in order to fulfill the objectives of sustainable development. Sustainable production via the alternative machining technologies, namely cryogenic and high pressure jet assisted machining is promoted because these technologies have a high potential to cut costs and improve competitiveness by reducing resource consumption, thus creating less waste. The general issues of sustainable technologies are pointed out with a comparative case study LCA performed for alternative machining processes, concluding that the future of sustainable production is going to entail the use of alternative machining technologies to reduce consumption rates, environmental burdens, and health risks simultaneously, while increasing performance and profitability.

A study also carried out an experimental technology evaluation to discuss the importance of sustainable machining technologies in achieving sustainable development objectives and to study the outcomes of adopting such techniques which are sustainable [16]. A cost and benefit analysis was presented. The sustainability evaluation was done for cryogenic and high pressure jet-assisted machining while comparing them with conventional machining. The sustainability performance measures used in the study refer to environmental impact, energy consumption, safety, personal health, waste management, and cost. The case-study refers to the machining of high-temperature Ni-alloy (Inconel 718). It is shown that tooling costs represent the major contribution to the overall production cost, which contradicts previous analyses, and that sustainable machining alternatives offer a cost-effective route to improving economic, environmental, and social performance in comparison to conventional machining. The disadvantages of initial high price and effort are also discussed along with the payback periods and the improvement in productivity.

Gustowski *et al.* [17] pointed towards a new dimension in sustainability measurement by proposing the adoption of a thermodynamic approach considering the ecosphere is adapted to come up with a model of our system of interactions in the modern world. The general widespread notion of the world acting in a sustainable way is challenged. Sustainability was taken as defined by the UN. The idea of bio mimicry and industrial ecology is promoted for incorporating sustainability. It is suggested that for the model proposed by equations from thermodynamic principles, the mass, energy and entropy changes can be expressed as exergy and the value of the non-conserved exergy can serve as one of the metrics for sustainability regarding a particular system. However, it is argued that is not possible to come up with a single metric for sustainability assessment.

Gustowski *et al.* [18] proposed a thermodynamic framework, arguing that thermodynamics is well suited to analyze the magnitude of the effects of manufacturing processes on the environment and sustainability. It is also stated that such a framework would be helpful in determining the related efficiencies of the processes. Starting from the conventional mass and energy balance, the framework is based upon exergy analysis and hence derived accordingly. After that, electrical energy utilization is discussed and then a couple of model manufacturing process case studies are solved based on the derived model. What is intriguing though is that no machining process is discussed as a case study although data charts showing trends for it are present. It would have been interesting to see the above mentioned framework in action for the thermodynamic complexities of a machining process as a case study using the exergy model. The reason may be the fact that this paper in itself is somehow a ground-breaking effort and not much study has been done on the subject before. Also, earlier the stress has been on product quality rather than sustainability, so it may take some time to apply the model thoroughly to machining.

Gustowski *et al.* [19] also discussed various manufacturing processes and used literature to plot their electrical energy consumption data. The model proposed for analysis is exergy-based and the power required is given in terms of a relation. It is argued by showing the graphical trends of practical data for different manufacturing processes and the power relation that it is wrong to assume the specific energy requirement of a process as a constant. This value depends on the material processing rate of the process and hence the electrical energy requirements are also dependent on the processing rates. Data regarding machining scenarios is also given showing energy consumption of the processes, but how to measure the output exergy value still remains a question. It is later proposed using the plots and data that the energy consumption can be decreased by either improving the support systems of a process or by increasing the material processing rate.

Jesweit *et al.* [20] proposed the use of the Carbon Emission Signature (CESTM) for measuring the environmental burden of a manufacturing process. It is only required to use the CESTM of the power grid being used by the manufacturing setup and then it can be multiplied to the total energy consumed for the total part production by that setup. Also the concept of a Carbon Emission Label is introduced.

Fiksel *et al.* [21] discussed the progress in the relatively new field of sustainability performance measurement (SPM) and the principles and best practices of the process in detail. It is stated that incorporating sustainability leads to economic growth of a firm as well. The four basic principles of sustainability measurement are given. These principles cover the attention for both resource and value indicators, representing the triple bottom line of economic, environmental, and societal aspects, full consideration of the product life cycle, and the idea of leading (outcome) and lagging (business process) indicators, respectively. The best practices of five big industry clients have been shown as application models developed on the given principles. Sustainability metrics can be classified as qualitative or quantitative, absolute or relative. However, they should best represent the system at hand.

Feng *et al.* [22] discussed the concept of sustainable development while providing an overview of the metrics currently in use for measuring sustainability. The characteristics of these metrics are listed, which are quite similar to those presented in other studies and their importance is discussed. In addition to this, the current major categories of sustainability indices are discussed with respect to the organization that uses them, e.g., Ford’s PSI, OECD toolkit, Dow Jones sustainability index, General Motors metrics for sustainable manufacturing, Environment Pressure index for Europe, UN-CSD, Wal-Mart index, etc. However, most of these indicator sets are not for products and processes and there is currently a demand by the industry for such indices. This requires an infrastructure including indicator repository and complete guidelines. The metrics can be life-cycle activity-based or can be based on organizational levels. An illustration of an important life-cycle phase, manufacturing, shows the need for a set of metrics to analyze its sustainability.

Deiab *et al.* [23] investigated the effect of different coolant strategies on tool performance during turning operations on a specific grade of hardened steel. The coolant techniques included flood cooling, minimum quantity lubrication and cryogenic machining. Coated carbides were used as the cutting tools under observation. The cutting forces and the tool flank wear progression were predicted using artificial neural network (ANN) models. The study revealed that cryogenic machining gave encouraging results in terms of the tool wear and the energy consumption perspective. Also, the use of flood cooling resulted in hardening up the material which raised the forces and power required of the process. It was visible that the ANN models were sufficiently convenient in terms of predicting the tool wear and cutting forces and propose a modeling alternative to other techniques like ANOVA where statistical tools are used to analyze the effect of variation of parameters.

1.2.2 Environmentally Benign Lubrication Strategies

As established earlier, sustainability has to be incorporated at all three levels: social, economic and environmental. For machining processes, this is not complete without the cutting process lubrication taken into account. Huge amounts of cutting fluids consumption have been recorded in different countries, e.g. 100 million gallons a year in the U.S. and 75491 tons in Germany. In Japan very high consumption and disposal costs were recorded [24][25]. An estimate suggests that almost 16% of the total manufacturing costs are comprised of cutting fluid costs and when it comes to the machining of hard-to-machine materials, they reach up to 20-30 percent [26],[16]. Shokrani *et al*. [27] reviewed a considerable amount of working terms of environmentally conscious machining. Most cutting fluids are not biodegradable and contain various components, which can cause environmental and health hazards. Dangerous bacteria can grow and mix with the shop floor environment allowing dangerous biocides to be present. Moreover, the frequently used mineral oil is carcinogenic and can cause skin cancer. Chlorinated and sulphurized additives are also present in the shop-floor. The vaporized particles of such cutting fluids can be readily inhaled by workers and cause severe damage while their smell can make the work conditions uncomfortable [27], [28].

Zhang *et al*. [28], studied the effect of using minimum quantity cooled lubrication (MQCL) for down-milling of Inconel 718. It is stated that due to environmental concerns, sustainable machining technologies need to be used for machining. MQL is often used but the low cooling capacity of air is a limitation to the utility of MQL. However, refrigerated air can be used as a remedy in this regard. A study was executed using MQCL with bio degradable vegetable oil dry machining strategies. It was revealed that similar tool wear mechanisms showed up while using either the dry or MQCL technique. However, the tool life increased by 1.57 times under MQCL. MQCL also offered lower cutting forces due to better cooling and lubrication performance. Moreover, with 100% biodegradability and no uncomfortable effects like bad smell, MQCL turns out to be a more sustainable alternative to both conventional MQL and dry machining.

Siniawski *et al*. [29] stated that dry machining and minimum quantity lubrication are promising lubrication techniques that need to be considered for new machine tool systems. While dry machining is the ultimate goal, MQL will always be a key method to introduce nearly dry machining. In particular, for systems where a single machine tool is used for one component, these technologies propose significant financial and environmental incentives. It is also important to introduce environmentally safe lubricating fluids that possess both good biodegradability and lubrication properties as MQL fluids.

Pusavec *et al*. [30] proposed cryogenic machining as a sustainable machining strategy. The challenges that the future of sustainable machining faces in terms of competitive production and environmental hazards are established. An LCA of the Cooling Lubricating Fluids (CLFs) is executed. The LCA revealed the significant potential of cryogenic machining using liquid nitrogen (LN). The solid waste, acidification and water usage would be reduced along with the global warming potential. A comparative analysis between cryogenic and conventional machining in terms of total production energy consumption shows that cryogenic machining is more energy efficient because of high-energy consumption from tool production, even though it appeared otherwise based on the nitrogen extraction energy burden.

Safian *et al*. [31] evaluated the use of biodegradable vegetable oil as an alternative cutting lubricant. While the vegetable oil was used through the MQL technique, the vegetable oil was compared with the dry and flood cooling strategies using coolant with emulsion. The various machining trials for end-milling AISI 420 hardened stainless steel revealed that the vegetable oil used through MQL produced the best results in terms of tool life. The study also showed that the effects of the cutting fluid and type of adopted cooling strategy on tool life and tool wear were significant. The results thus showed the vegetable oil MQL as a viable alternative to wet and dry machining.

Burton *et al*. [32] stated that the development and evaluation of vegetable based metal working fluids or MWFs has been the subject of a considerable amount of research in recent years. The emulsification of vegetable oil in water is also an interesting area of research. Studies revealed that not only stable emulsification of canola vegetable is achieved, but a reduction in cutting forces, chip thickness and burrs is observed in end-milling operations.

Venugopal *et al*. [33] studied the effect of cryogenic cooling on the nature and growth of tool wear in uncoated carbide cutting tools while turning titanium Ti-6Al-4V. The importance of this study lies in the increased demand of titanium alloys in various biomedical, engineering and other applications. Since it is a hard-to-machine material, the main challenge in machining titanium is the rapid tool wear encountered. Liquid nitrogen jets are used in comparison with dry and wet machining strategies. The wear mechanisms were significantly reduced under the effect of cryogenic cooling, thus promising environmentally safe machining with better productivity.

Bermingham *et al*. [34] indicated that adopting technologies such as cryogenic coolants and high pressure emulsions is difficult for the industry because of the lack of direct comparison research. Various benefits of both technologies, cryogenic coolant and high pressure emulsion, have been identified for turning Ti-6Al-4V. While both techniques turned out to be effective coolants extending the tool life, the high-pressure water based emulsion offers a slightly better tool life. The high-pressure emulsion also penetrated deeper into the tool-chip interface and produced smaller chips. It was noted that the method of coolant delivery is of prime importance since the optimization of nozzle position can in some cases improve tool life by up to 80 percent.

Cetin *et al*. [35] stated that vegetable based cutting fluids can replace the conventional cutting fluids. It was expected that vegetable oils with extreme pressure additives (EP) would perform better in terms of reduction of tool wear, surface roughness and cutting forces. A Taguchi method study was executed with six different cutting fluids that involved sunflower and canola oil based cutting fluids with 8 and 12 percent EP additive (all with bio-degradability greater than 95 percent) and two commercial cutting fluids of semi-synthetic and mineral types. The turning experiments on AISI-304L aluminum indicated that both the sunflower and canola cutting fluids with EP additives were the better option for cutting and feed forces. For surface roughness, canola based fluid with EP additives and sunflower based fluid without EP additives gave the best results. This confirmed the superiority of vegetable oils over commercial cutting fluids.

Fratila *et al*. [36] used the Taguchi method to execute a parametric study to determine the optimum cutting and lubrication conditions for face-milling of $AlMg_3$. Three lubrication strategies, namely flood, dry and MQL were used. The outputs of interest were surface roughness and cutting power. Although dry machining gave better surface roughness, the cutting power was less when flood cooling was used. Authors noted that in neither case did MQL drastically challenge the optimal conditions or show much negative effect on surface quality and cutting power.

Lawal *et al*. [37] reviewed various lubrication techniques for machining processes and stated that it was impossible to rank them based on the variety that lies in the work piece, tool materials and the process itself. Nevertheless, a detailed analysis revealed that the MQL technique still holds an edge. The air/vapour /gas technique needs more research to verify its suitability. The high-pressure coolant needs more research since the process is not well understood and the available literature is restricted to hard-to-machine materials. Cryogenic machining has shown promise in terms of quality and performance. Although it has high initial costs, it provides effective long-term solutions for coolant disposal and chip recycling. The MQL technique with vegetable oil as a lubricant apparently offers the best environmental solution coupled with improved performance as observed by researchers.

Kuram *et al*. [38] tried to optimize the cutting parameters and lubrication by using a D-optimal response surface-based design of experiments. Milling operations on AISI-304L aluminum were conducted using canola and sunflower-based vegetable oils with different percentages of EP additives. It was concluded that a canola-based cutting fluid with higher EP additives is more suited for energy consumption since it yields lesser specific energy. However it gives lesser tool life than sunflower oil-based cutting fluid with higher EP additive content. If surface roughness and total cost are also considered, then the canola-based cutting fluid with higher EP additives gives an overall better performance.

Andriya *et al*. [39] explored the cutting parameter settings for turning Ti-6Al-4V using PVD-coated TiAlN cutting tools under dry machining conditions. The study was focused on exploring the range of cutting force magnitudes and surface roughness. For surface roughness, cutting velocity and feed were the most significant.

Alves *et al*. [40] proposed the use of vegetable oil-based cutting fluid to address the scarcity of mineral oil and the potential pollution caused by commercial cutting fluids. A new formulation of 40% sulphonate caster oil in water was proposed. A comparison was made for grinding operations using neat oil, semi-synthetic oil and the new vegetable oil-based formulation. It was concluded that the new formulation not only resulted in good performance but was readily bio degradable and proved to be a good corrosion inhibitor for the work piece.

Weinert *et al*. [41] stated that the minimum quantity cooling lubrication (MQCL), unlike MQL, has not been widely used and that further investigation is needed. The MQCL system holds a lot of potential for the future of efficient and safe machining. While machining systems equipped with MQL, cryogenic or dry machining are available today, more improvements have to come in the lubrication process design in terms of delivery system, cooling and lubrication performance.

Kalyan Kumar *et al*. [42] compared dry machining with cryogenic machining and observed a reduction in cutting forces by 14.83%. Cryogenic machining outperformed dry cutting by 37.39% in terms of flank wear. Nevertheless, the N_2 consumption was high, making the process expensive.

Hong *et al*. [43] found that cryogenic machining using LN2 tends to increase the cutting force when machining Ti-6Al-4V. This can be related to the hardening of the work-piece at lower temperatures, which in turn is responsible for reducing the frictional force. Thus, the reduction in feed force and the thickness of the secondary deformation layer in the microstructure of the chips, along with the appropriate coefficient of friction make LN2 a suitable lubricant.

In summary, a review of the open literature sources reveals that the energy consumption of a manufacturing process emerges on top of time, cost and quality as a very important metric of sustainability. These reviewed studies show again that cost and energy consumption or foot-print are two very significant indicators regarding the sustainability of a machining process. Also, the optimization of the machining conditions can be very helpful in the design and development of the test-case studies later proposed in this document. Although some of these studies propose a promising method to measure process sustainability, they are still in a preliminary stage and do not offer a practical model for measuring sustainability of cutting processes in particular. However, this provides useful resources for tracking the energy consumption of a process, which is of great interest currently and might also be helpful in a more advanced and futuristic model of sustainability assessment mechanisms. In addition to energy and time consumed, the cost of different sections appears to be a good comparative metric for the sustainability calculator. Tool cost and tool life are very important in this regard. It is also seen that during the life cycle of a product, the manufacturing phase, or the use phase of the machine tool, is very important and needs to be studied. It is important to note that the metrics selection or building process proposed in the literature is very significant to the approach that shall be adopted for the study at hand. Taking out the ones which are not directly related to the area of focus for sustainability in this study, the rest of the approach is discussed further.

- Creating a list of “reference metrics” by reviewing the work that has been done by others.
- Considering additional metrics that are considered important from any perspective.
- Examining all the proposed metrics and then coming up with a list that evaluates all major aspects of sustainability to a reasonable extent with completeness and coherence.
- Specifying the detail of what must be measured and how so that meaningful numbers are achieved that can be compared with some standard or existing work, if possible.
- Devising a way to normalize the measured quantities so that indexes are independent actual process parameter quantities.

The review also provides a basis for developing test-case studies for sustainable machining processes. It appears that vegetable oil lubrication and cryogenic machining are also good techniques to be tested in case studies. The performance measures adopted are very useful to be added and compared with our general pool of sustainability indices at the end of this literature review. Thus it could be seen in the end that a set of designed experiments has to be conducted to analyze the machining performance under different circumstances from a sustainability perspective. The sustainability calculator will be used to help predict the results and try to develop practical compatibility for the calculator.

1.3 Research Methodology

The technical approach to achieve the aforementioned objectives was developed in a step-by-step manner. Different activities were segregated into project phases to enable parallel commencement. The project outline can be described by the following phases.

1.3.1 Phase-I: Literature Survey

A literature survey on metrics and methods of evaluation used to assess sustainability of machining process is conducted. Different databases and other available resources are tapped in order to learn about the current methods to evaluate the sustainability of a machining process.

1.3.2 Phase-II: Analysis of Metrics

Analysis of the different metrics and methods available in the literature is conducted. This is so that relevant metrics and methods for sustainability calculation can be selected after agreement and a collection of general metrics and methodologies can be created.

1.3.3 Phase-III: Selection of Metrics

In this phase a pool of metrics to be used is selected to develop the calculator. This will be a carefully selected set of metrics out of the general collection. The metrics selection has to be justifiable. The literature survey reveals that the energy consumption of a manufacturing process emerges on top of time, cost and quality as a very important metric of sustainability. It can later contribute in many ways, like being incorporated in CAPP (computer-aided planning), asset management, and most importantly in environment burden assessment and productivity. In addition to energy and time consumed, the cost of different sections appears to be a good comparative metric for the sustainability calculator. Tool cost and tool life are very important in this regard. Since metric selection (building process) is very important, only those metrics which are directly related to the areas of focus in sustainability would be chosen from the literature.

Phase-IV: Developing the Calculator

Using and building upon the data extracted from previous phases, the sustainability calculator will be developed taking into consideration a selected set of generic input parameters and evaluating response indicators. This will enable us to rate a given process in terms of sustainability. It is to be noted that as soon as certain metrics are agreed upon, the structure development of the calculator shall start. While the review is still under progress, changes shall then be made as and when required.

Phase-V: Test Case-studies / Experimental work

The design of experiments is used to develop a test matrix to collect the needed data. The test matrix is a set of designed experiments through the prevalent DoE techniques that study the output responses like the material removal rate, cutting time, surface quality, dimensional accuracy, tool wear etc. through standard input machining parameters like cutting speed, feed rate, depth of cut etc. under different scenarios that involve either variations in the cooling method (dry cutting/MQL/ cryogenic) or cutting tool materials. The idea is to get output responses, evaluate them against sustainability responses like energy consumption, carbon emission, cost etc. of the processes, and then analyze the system using our proposed sustainability indicators and check how well they portray the sustainability status of the scenario in the light of the literature survey.

The activity involves using the LCA sustainability calculator for the machining phase. One shall be able to check the compatibility of the sustainability indicators calculated solely from the calculator and those that are based on measured response values, which are input into the calculator directly. Finally, recommendations for further enhancement of the calculator can be made along with an analysis of the effectiveness of the selected sustainability metrics.

Phase-VI: Process evaluation, Debugging and Reviewing

In light of the case study evaluation and results, the proposed and agreed upon changes in the calculator will be made and if necessary, further test runs may be performed so that a finalized format and structure is achieved. The calculator should then be able to rate a process and be helpful for recommending improvements or verifying the recommended improvements.

2. Measuring Machining Process Sustainability

Machining is a collection of metal removal processes in which power-driven machine tools, such as lathes, milling machines, and drill presses, are used with a sharp cutting tool to mechanically cut the material to achieve the desired geometry by straining the material to fracture and by thermal evaporation. Machining is a part of the manufacture of almost all metal products, and it is common for other materials, such as wood and plastic, to be machined. The precise meaning of the term "machining" has evolved over the past 1.5 centuries as technology has advanced. During the Machine Age, it referred to the "traditional" machining processes, such as turning, boring, drilling, milling, broaching, sawing, shaping, planing, reaming, and tapping, or sometimes grinding. Since the advent of new technologies such as electrical discharge machining, electrochemical machining, electron beam machining, photochemical machining, and ultrasonic machining, the retronym "conventional machining" can be used to differentiate the classic technologies from the newer ones [44],[45],

While the word “sustainability” usually refers to keeping in existence or maintaining, the United Nations’ Brundtland Commission defines sustainability as:

“Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

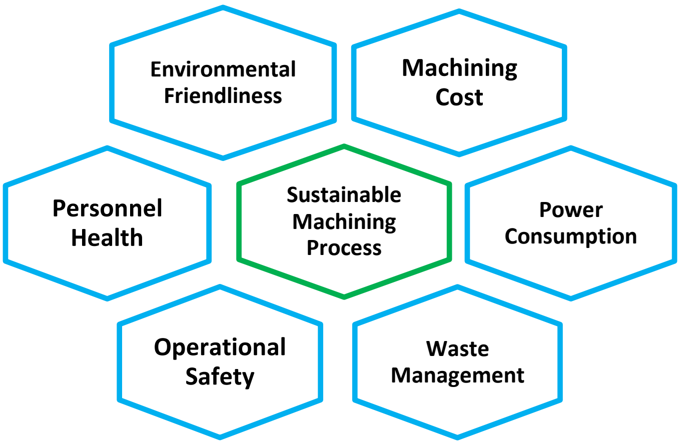


Fig. 1 Basic Elements of Sustainable Machining. [11]

It was established through the literature review that for a process to be deemed ‘sustainable’, it should have less environmental burden, be positive for the society and be economically sound. This is often shown as the elements of sustainable machining shown in Fig. 1. But for knowing about the extent of sustainability a process possesses, it is necessary to rate it. However, rating a system for sustainability can be quite cumbersome. Thus a set of limited metrics is required that can cover the diverse aspects of sustainability as much as possible and enable informed decision making for the product or process design engineers. The importance of rating the machining processes in this regard can be hardly over-stressed [1]–[5].

Thus the approach developed includes creating a list of “reference metrics” by reviewing the literature and considering additional metrics while examining all the proposed metrics. This also includes the details of what must be measured and devising a way to normalize the measured quantities so that indexes are independent of process types. In the end it was observed through the literature review that the energy consumption of a manufacturing process emerges on top of time, cost and quality as a very important metric of sustainability. In addition to energy and time consumed, the cost of different sections appears to be a good comparative metric and cost and tool life are very important in this regard. It is also seen that during the life cycle of a product, the manufacturing phase, or the use phase of the machine tool, is very important and needs to be studied.

2.1 Sustainability Metrics: The XSI-Approach

While the sustainability concept emphasizes a holistic and synergistic approach through techniques like LCA of a product, meaningful results cannot be achieved unless phases like machining are rated for sustainability in detail. The machine tool scale is one level in the scope of analyzing sustainability [46]. Open literature sources reveal that the machining sector needs not just one but a set of flexible, easy-to-use and meaningful sustainability indicators.

These indices should not only cover different perspectives for sustainability (e.g., coolant use, machining cost, energy consumed, CO_2 emission, etc.) but also the features of interest for the organization doing the production (material removal rate, MRR, surface roughness, etc.). To develop the metrics with such qualities, an XSI-approach is proposed, where X represents a given perspective for sustainability. To achieve flexibility for comparison of various processes, the concept of normalization is introduced [47], [48]. Hence a quantity like the environmental burden of machining (kgCO2), can be divided by a feature of interest like MRR, to become the Carbon Sustainability Index (CSI) which can be used to rate both turning and milling processes. Similarly, the Financial Sustainability Index (FSI) and Energy Sustainability Index (ESI) can be calculated. Such a set of indices can give insight regarding process and parameter selection in a quantitative manner.

The material indices development process for material selection using performance equations can be very helpful in this regard [49], [50]. In fact, the proposed XSI approach is very similar to the latter. It appears that by taking inspiration from the material indices, the normalized values should be inversed when required. This would present a “the higher the better” scenario for quantities that we want to minimize. Thus the results will be easier to interpret. In later case studies, a demonstration of this concept is presented.

3. Development of the Sustainability Calculator

As mentioned in the research methodology, the next step after reviewing the sustainability indicators is the development of a sustainability calculator based on the proposed XSI approach. This calculator would not only be a tool for rating the sustainability of machining processes individually but would also be able to contribute to the LCA of a certain product. Hence whether a product made by machining is under examination of its "manufacturing" phase or a machine tool is reviewed for its "use" phase, this tool shall find its application. The developed sustainability calculator uses the selected sustainability indicators to evaluate a process. The calculator uses the idea of using emission intensities for evaluating environmental burden for electricity consumption and coolant usage as done by Narita *et al*. [13]. It also shows the material removal rate and the cost of machining. The values thus found after taking different factors into account are then normalized by the material removal so that a uniform application for all conventional processes is ensured for the calculator. Thus a set of new sustainability indices or metrics is proposed.

The calculator uses the user-defined input parameter values to calculate different quantities related to machining like the material removal rate, the energy consumed and the amount of coolant used. These values are taken as intermediate values and are then further converted into a set of proposed forms of selected sustainability indicators. These include values like the Energy Sustainability Index (ESI), the Financial Sustainability Index (FSI), the Environmental Sustainability Index (EnSI) and the Coolant Sustainability Index (CoSI). The proposed form is the normalization with the feature of interest, which in this case is the material removal.

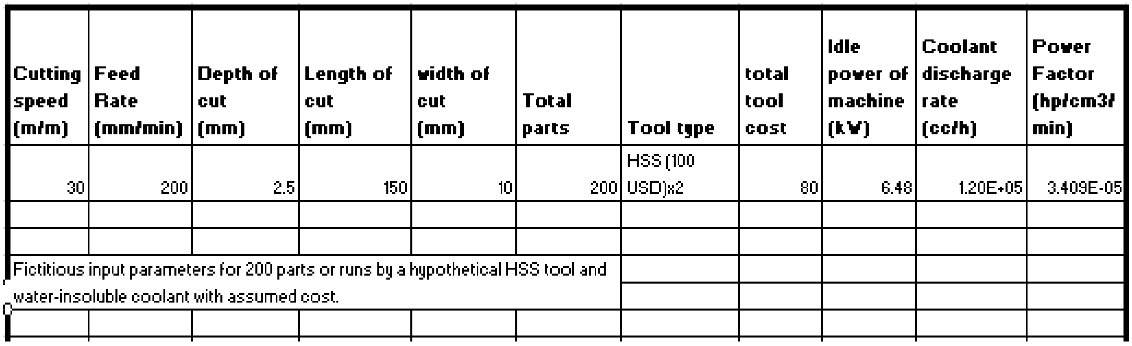
The environmental burden of different segments of the machining process under study is used by the multiplication of the quantity of the resource used with its respective emission intensity. The set of emission intensity values, based on a Japanese energy mix and used in the calculator for rating purposes, is given in Table 2 [13].

Table 2 Emission Intensities [13]

Electricity (kg-CO2/kWh)	0.381
Cutting fluid production(kg-CO2/L)	0.469
Cutting fluid disposal, water-miscible cutting fluid; type A1 (kg-CO2/L)	3.782
Cutting fluid disposal, water-miscible cutting fluid; type A2 (kg-CO2/L)	5.143
Cutting fluid disposal, water-miscible cutting fluid; type A3 (kg-CO2/L)	8.103
Cutting fluid disposal, distilling and condensing process (kg-CO2/L)	3.425
Cutting fluid disposal, water-insoluble cutting fluid; normal (kg-CO2/L)	2.555
Cutting fluid disposal, water-insoluble cutting fluid; thermal recycle (kg-CO2/L)	1.778
Cutting fluid disposal, water-insoluble cutting fluid; material recycle (kg-CO2/L)	0.261
Dilution fluid, water (kg-CO2/L)	0.189
Spindle and slideway lubricant oil production (kg-CO2/L)	0.469
Spindle and slideway lubricant oil disposal (kg-CO2/L)	0.0029
Cutting tool production (kg-CO2/kg)	33.7478
Cutting tool disposal(kg-CO2/kg)	0.01346
Re-grinding (kg-CO2/number)	0.0184
Metal chip processing (kg-CO2/kg)	0.0634

A first version of the calculator was developed using Microsoft Excel, which covers the set of values being input, the response quantities and the sustainability indices calculated from them. Later on a user-friendly Graphical User Interface (GUI) was developed using Visual Basic Studios and .Net code. Efforts then commenced to develop a more inter-active, user-friendly and flexible module using MATLAB. The environmental burden was calculated using the emission intensities provided in [13] and [51]. Also, the costs of machining were based on the UAE tool market and [52]. The process details were given as a set of input parameters. The calculator computes the energy consumption through empirical formulas and evaluation of the tool path from the NC-code along with idle-power considerations [53]. Together the set of input parameters and output responses yield the sustainability indices, thus rating the process. Figure 2-5 depicts various versions of the calculator.

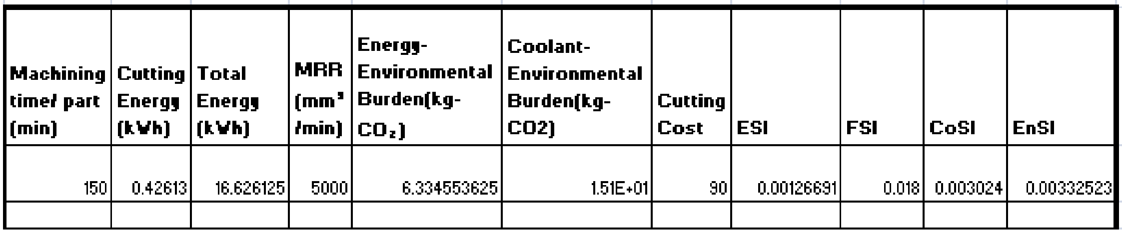
Inputs



Cutting speed (m/m)	Feed Rate (mm/min)	Depth of cut (mm)	Length of cut (mm)	width of cut (mm)	Total parts	Tool type	total tool cost	Idle power of machine (kW)	Coolant discharge rate (cc/h)	Power Factor (hp/cm3/ min)
30	200	2.5	150	10	200	HSS (100 USD)x2	80	6.48	1.20E+05	3.409E-05

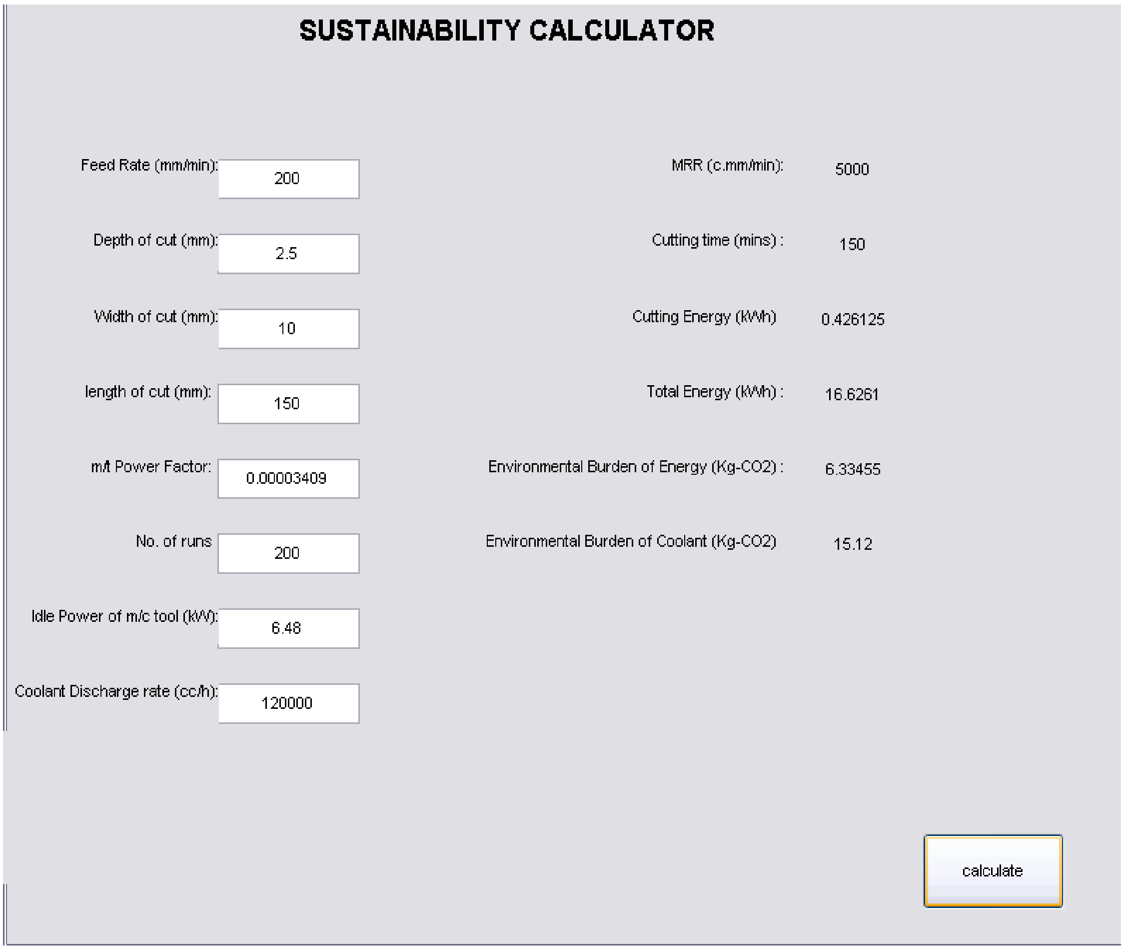
Fictitious input parameters for 200 parts or runs by a hypothetical HSS tool and water-insoluble coolant with assumed cost.

Outputs



Machining time/ part (min)	Cutting Energy (kWh)	Total Energy (kWh)	MRR (mm³ /min)	Energy-Environmental Burden(kg-CO₂)	Coolant-Environmental Burden(kg-CO2)	Cutting Cost	ESI	FSI	CoSI	EnSI
150	0.42613	16.626125	5000	6.334553625	1.51E+01	90	0.00126691	0.018	0.003024	0.00332523

Fig. 2 Sustainability calculator: Excel format



SUSTAINABILITY CALCULATOR

Feed Rate (mm/min): 200
Depth of cut (mm): 2.5
Width of cut (mm): 10
length of cut (mm): 150
m/t Power Factor: 0.00003409
No. of runs 200
Idle Power of m/c tool (kW): 6.48
Coolant Discharge rate (cc/h): 120000

MRR (c.mm/min): 5000
Cutting time (mins) : 150
Cutting Energy (kWh) 0.426125
Total Energy (kWh) : 16.6261
Environmental Burden of Energy (Kg-CO2) : 6.33455
Environmental Burden of Coolant (Kg-CO2) 15.12

Fig. 3 MATLAB-GUI, first-look.

In itself, the sustainability calculator shall be able to predict the implications of using a specific machine setting using a set of particular machining parameters and cutting scenarios along with cooling configurations on the sustainability of the machining process. Thus it will be providing the user with important information about the feasibility of the process from different perspectives. This information shall be useful in evaluating the machining phase of the life cycle of a product hence making this calculator an LCA support tool. Although different in the method of evaluation and usage, it takes part of its inspiration from virtual machining models for sustainability analysis and financial models for GHG emissions proposed earlier [54],[55].

SUSTAINABILITY CALCULATOR

Enter the cutting parameters, machine and material specs; Press CALCULATE.

millig

Cutting Speed (m/min): 30
Feed Rate (mm/min): 200
Depth of cut (mm): 2.5
Width of cut (mm): 5
length of cut (mm): 1000
m/t Power Factor: .00003409
No. of runs 200
Idle Power of m/c tool (kW): .37
Coolant Discharge rate (cc/h): 120000
Machining Cost ($): 90
X-motor Rating (KWh/mm): .028304

MRR (c.mm/min): 2500
X-Travel (mm) : 1023
Cutting time (mins) : 1000
Cutting Energy (kWh) : 1.42042
Total Energy (kWh) : 7.58708
Dry run energy (KWh :) 7.64214
Environmental Burden of Energy (Kg-CO2) : 5310.96
Environmental Burden of Coolant (Kg-CO2) : 100800
Energy Sustainability Index (ESI) : 2.12438
Coolant Sustainability Index (CoSI) : 40.32
Financial Sustainability Index (FSI) : 0.036

SUSTAINABILITY CALCULATOR

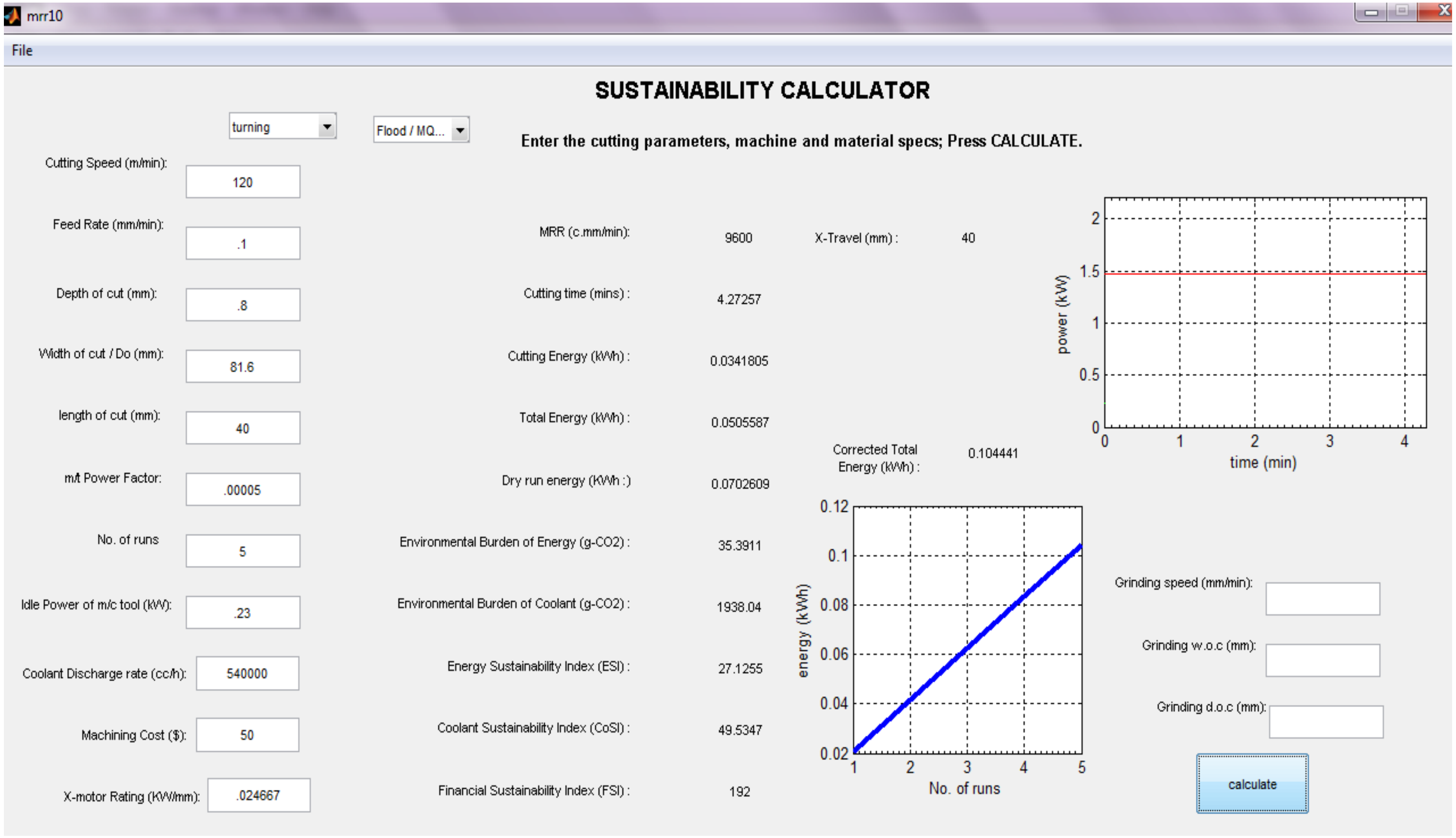
Enter the cutting parameters, machine and material specs; Press CALCULATE.

turning

Cutting Speed (m/min): 120
Feed Rate (mm/min): .1
Depth of cut (mm): .8
Width of cut / Do (mm): 95.2
length of cut (mm): 50
m/t Power Factor: .00005
No. of runs 1
Idle Power of m/c tool (kW): .27
Coolant Discharge rate (cc/h): 540000
Machining Cost ($): 50
X-motor Rating (KWh/mm): .020406

MRR (c.mm/min): 9600
X-Travel (mm) : 50
Cutting time (mins) : 1.24617
Cutting Energy (kWh) : 0.00996932
Total Energy (kWh) : 0.0155771
Dry run energy (KWh :) 1.0203
Environmental Burden of Energy (g-CO2) : 10.9039
Environmental Burden of Coolant (g-CO2) : 565.26
Energy Sustainability Index (ESI) : 1.13583
Coolant Sustainability Index (CoSI) : 5.88813
Financial Sustainability Index (FSI) : 0.00520833

Fig. 4 MATLAB-GUI, later versions.



SUSTAINABILITY CALCULATOR

Enter the cutting parameters, machine and material specs; Press CALCULATE.

Cutting Speed (m/min): 120

Feed Rate (mm/min): .1

Depth of cut (mm): .8

Width of cut / Do (mm): 81.6

length of cut (mm): 40

m/t Power Factor: .00005

No. of runs 5

Idle Power of m/c tool (kW): .23

Coolant Discharge rate (cc/h): 540000

Machining Cost ($): 50

X-motor Rating (KW/mm): .024667

MRR (c.mm/min): 9600

X-Travel (mm) : 40

Cutting time (mins) : 4.27257

Cutting Energy (kWh) : 0.0341805

Total Energy (kWh) : 0.0505587

Corrected Total Energy (kWh) : 0.104441

Dry run energy (KWh :) 0.0702609

Environmental Burden of Energy (g-CO2) : 35.3911

Environmental Burden of Coolant (g-CO2) : 1938.04

Energy Sustainability Index (ESI) : 27.1255

Coolant Sustainability Index (CoSI) : 49.5347

Financial Sustainability Index (FSI) : 192

Grinding speed (mm/min):

Grinding w.o.c (mm):

Grinding d.o.c (mm):

Fig. 5 MATLAB-GUI, final version.

4. Turning of Titanium Alloy Ti-6Al-4V

4.1 Titanium Alloy Ti-6Al-4V

Titanium has become a very important material in manufacturing these days because of its high strength-to-weight ratio in addition to its characteristic corrosion resistance which is highly reliable in various fields of application. The use of titanium brings with it durability, reliability and economic feasibility in industry applications. Especially in fields like the aerospace or automotive industry, along with surgical procedures where very highly reliable equipment is required, titanium turns out to be very useful. Other applications of a similar scale are also found in the oil and gas sector, industries like competitive sports goods manufacturing, chemical industry facilities and power plants. In the majority of these and other engineering applications titanium has replaced heavier, less serviceable or less cost-effective materials. Today various grades of titanium are available in the market offering a range of desired characteristics. Titanium alloys like Ti-6Al-4V offer better strength than pure titanium [56], [57].

Due to its excellent machinability and mechanical properties, Ti-6Al-4V is today the titanium alloy that finds its application most widely in various fields. It offers very good bio-compatibility in bone and tissue contact scenarios. For different cases where the reduction of weight is the area of focus, it is very useful in the marine, aerospace and automotive industry. Products as varied as gas turbines, biomechanical implants, prototypes and components for the racing industry find Ti-6Al-4V particularly useful. Mechanical properties of Ti-6Al-4V are given in Table 3 [56].

Table 3 Mechanical Properties of Ti-6Al-4V [56]

Ultimate Tensile Strength	1050 MPa
Fatigue Strength @600 MPa	100000 cycles
Rockwell hardness	33 HRC
Modulus of Elasticity	120 GPa

Due to the earlier established importance of titanium and its alloy Ti6Al4V, the importance of machining titanium is also significant. This is why this area is being researched across the globe and is the focus of this study. The study of assessing sustainability in turning titanium is divided into two sections. The first study includes the use of conventional and sustainable cooling and machining strategies varying many parameters involved. The second study focused on comparing environmentally-benign cooling strategies with a limited variation of other parameters.

4.2 Comparison of coolant and machining strategies' impact on machinability of titanium alloy Ti6Al4V

The first set of experiments was focused on comparing the effect of a coolant on the machinability of Ti6Al4V. The test matrix was a set of experiments designed through a prevalent DoE technique that studies output responses like the Material Removal Rate, Cutting Time, Surface Quality, Dimensional Accuracy, Tool Wear, etc. through standard input machining parameters like cutting speed, feed rate, depth of cut, etc. under different scenarios that involve either variations in the cooling method (dry cutting/MQL/cryogenic) or tool materials of different kinds. The idea is to get output responses, evaluate them against sustainability responses like energy consumption, carbon emission, cost, etc. of the processes, and then analyze the system using our proposed sustainability indicators and check how well they portray the sustainability status of the scenario in light of the literature survey.

The sustainability calculator designed for the machining phase shall be able to check the effectiveness of the calculator. While the hybrid machining scenario could be compared with conventional method without the indicators, the conventional process settings are to be evaluated separately, in terms of the indicators. Finally, recommendations for additions or subtractions for the calculator can be made along with an analysis of the effectiveness of the selected sustainability metrics.

To develop the test matrix a set of input factors for the Design of Experiments procedure was selected. These factors included the cutting speed, feed rate, the type of lubrication applied and the type of tool used. Against a combination of these factors, a parametric study of responses was carried out for two machining strategies: classical turning and grinding in sequence and a hybrid or combination machining process with simultaneous turning and grinding. The response values comprised the cutting time, the energy consumed, amount of lubricant consumed, the average tool life, the material removal rate and the surface roughness with prime focus on energy consumption. These values were then used for the computation of other output values that include the cutting cost and the respective environmental burdens which could be later converted to our proposed set of sustainability indices and later on evaluated for the proposed sustainability calculator.

4.2.1 Design of Experiments and Experimental Setup

The work-piece material selected for this study is titanium Ti6Al4V because of its high strength, important applications and the difficulty to machine it along with its various applications mentioned in Section 4.1. The cutting tool types would include a coated cemented carbide and an uncoated cemented carbide turning tool insert (Grade: H13A and GC1105 respectively). For grinding purposes, two Silicon Carbide wheels with a small grit size of 80 and a medium grit size of 100 would be used. The lubrication scenarios would involve flood cooling and a Minimum Quantity Lubrication machining scenario. Fig. 6 shows a schematic illustration.

The design technique selected for the DoE in this study is the half factorial technique. The reason is the fact that this method gives a reasonably clear representation of the system at hand. Also, the study involves six input parameters, all having two levels of variation (Fig. 7). The level values for quantified parameters have been selected for these quantities close to the prevalent literature quantities for manufacturing scenarios. This gives us a total number of 64 runs according to the full factorial design formula which may be practically unfeasible in our case. Hence the half-factorial scenario with 32 runs, as shown in Table 4, was selected. The values of the high (Hi) and low (Lo) levels were selected close to the prevalent machine settings [58].

Once the set of experiments is completed and a model is achieved using ANOVA, a more sophisticated study can follow. Based on the results of the ANOVA, the significant parameters of the study can be identified and hence they can be studied in more detail in a revised test matrix. For example, the lubrication technique can be extended to the usage of vegetable oil, cooled air and cryogenic machining along with

MQL and flood cooling, since they are all potentially sustainable alternatives for lubrication.

A dry run for the machine was also performed with no depth of cut to get the machine energy consumption rating for axis motion and coolant pump of an XL-Leader Model # BNC-2143X. Runs were conducted on this NC lathe to observe a challenging machining scenario by turning the titanium Ti4Al6v specimen. Fig. 6 shows the schematics of the process while Fig. 8 and Fig. 9 show photographs of both classical and hybrid turning, respectively. Given below is a G-code block for the dry run.

```
N010 T8                    (cutting tool call)
N020 M8                    (lubrication ON)
N030 S388 M3               (Spindle ON)
N040 G0 X100 Z1            (Workpiece Home)
N050 G01 G95 Z0 F.1        (Workpiece Home)
N120 Z-50                  (Cutting Travel)
N520 G0 X150
N996 M5 M9                 (Stopping Sequence)
N997 M30                   (Program Stop)
```

The Design Expert (8.0.7.1) package was utilized to carry out the design of experiments. The power consumption was recorded by using PowerSight Manager (PSM).

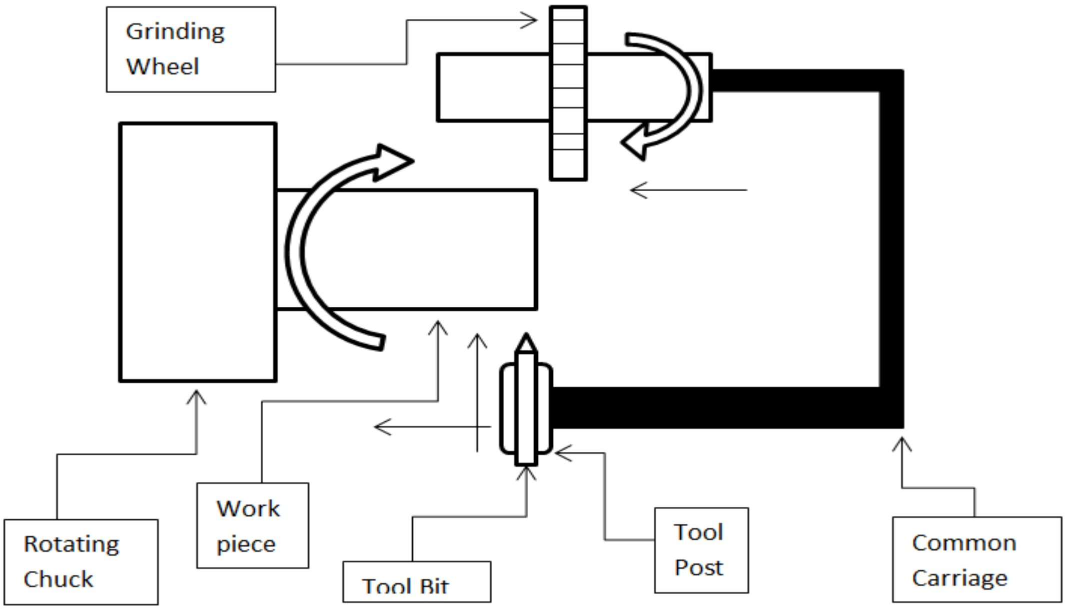


Fig. 6. Schematic of Hybrid Turning

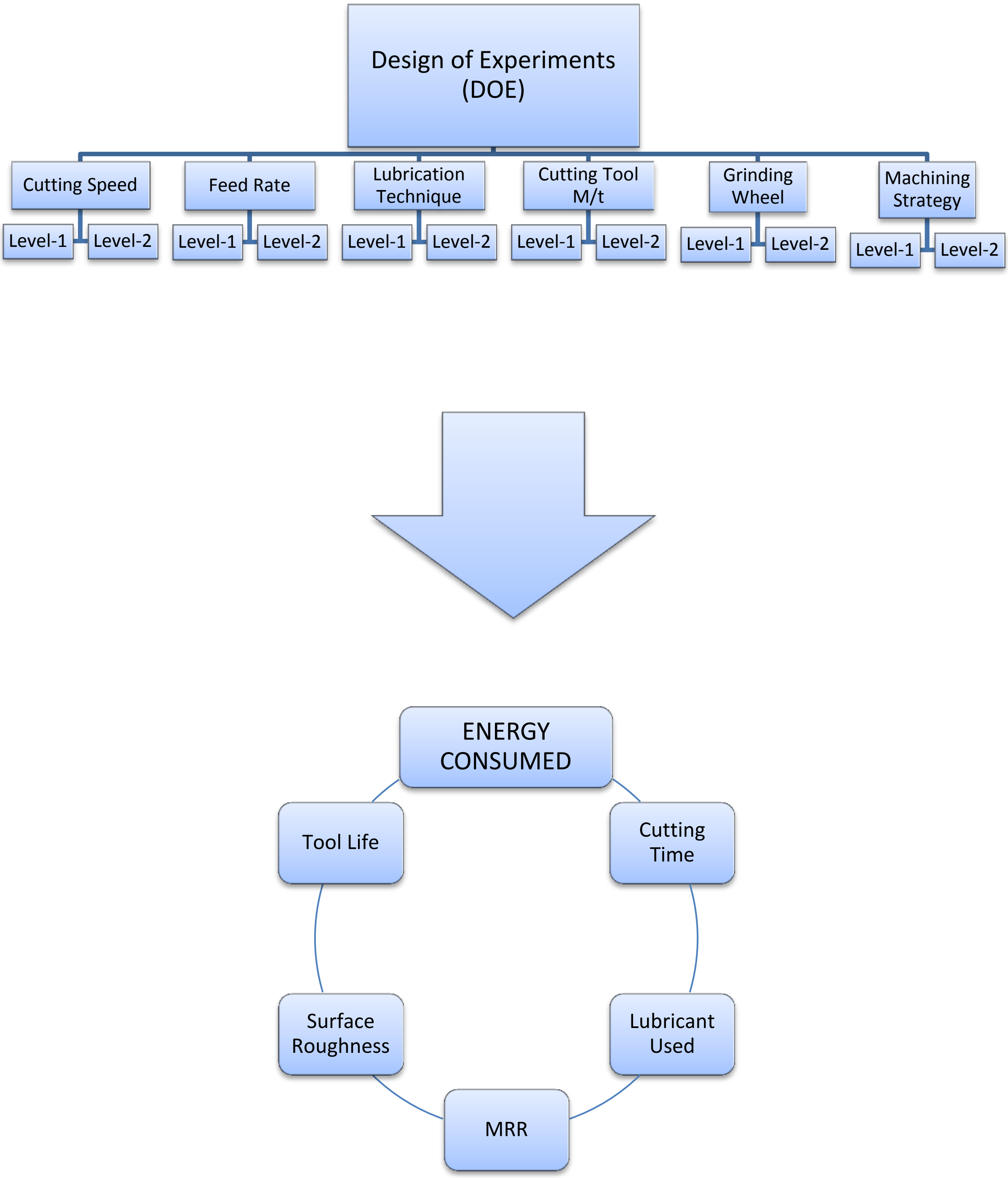


Fig. 7. Design of Experiments Framework for First Set of experiments.

After the randomization, the following design layout was created.

Table 4. Design Of Experiments.

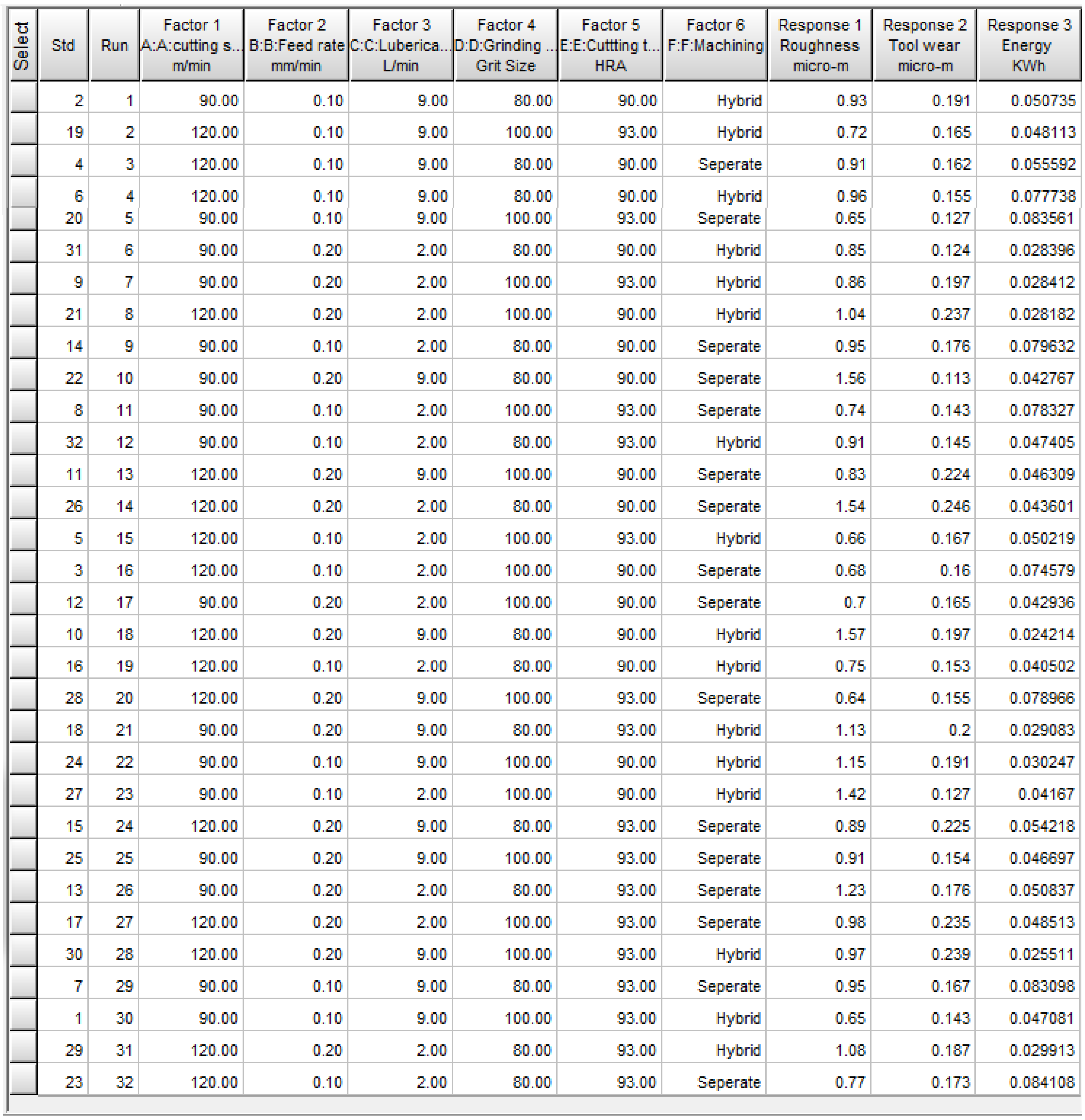
Run #	Cutting Speed (mm/min)	Feed Rate (mm/min)	Lubrication	Grinding Wheel	Cutting Tool	Machining Strategy
1	90	0.1	FLood	80s	H13A	Hybrid
2	120	0.1	FLood	100m	H13A	Hybrid
3	120	0.1	FLood	80s	H13A	Separate
4	120	0.1	FLood	80s	1105	Hybrid
5	90	0.1	FLood	100m	H13A	Separate
6	90	0.2	MQL	80s	H13A	Hybrid
7	90	0.2	MQL	100m	1105	Hybrid
8	120	0.2	MQL	100m	H13A	Hybrid
9	90	0.1	MQL	80s	H13A	Separate
10	90	0.2	FLood	80s	H13A	Separate
11	90	0.1	MQL	100m	1105	Separate
12	90	0.1	MQL	80s	1105	Hybrid
13	120	0.2	FLood	100m	H13A	Separate
14	120	0.2	MQL	80s	H13A	Separate
15	120	0.1	MQL	100m	1105	Hybrid
16	120	0.1	MQL	100m	H13A	Separate
17	90	0.2	MQL	100m	H13A	Separate
18	120	0.2	FLood	80s	H13A	Hybrid
19	120	0.1	MQL	80s	H13A	Hybrid
20	120	0.1	FLood	100m	1105	Separate
21	90	0.2	FLood	80s	1105	Hybrid
22	90	0.2	FLood	100m	H13A	Hybrid
23	90	0.1	MQL	100m	H13A	Hybrid
24	120	0.2	FLood	80s	1105	Separate
25	90	0.2	FLood	100m	1105	Separate
26	90	0.2	MQL	80s	1105	Separate
27	120	0.2	MQL	100m	1105	Separate
28	120	0.2	FLood	100m	1105	Hybrid
29	90	0.1	FLood	80s	1105	Separate
30	90	0.1	FLood	100m	1105	Hybrid
31	120	0.2	MQL	80s	1105	Hybrid
32	120	0.1	MQL	80s	1105	Separate

Fig.8 Sequential/Conventional turning and grinding.

Fig.9 Hybrid turning and grinding.

4.2.2 Results and Discussion

Following results were recorded for the study and were input into the design expert interface (Fig.10):



Select	Std	Run	Factor 1 A:A:cutting s... m/min	Factor 2 B:B:Feed rate mm/min	Factor 3 C:C:Luberica... L/min	Factor 4 D:D:Grinding ... Grit Size	Factor 5 E:E:Cuttting t... HRA	Factor 6 F:F:Machining	Response 1 Roughness micro-m	Response 2 Tool wear micro-m	Response 3 Energy KWh
	2	1	90.00	0.10	9.00	80.00	90.00	Hybrid	0.93	0.191	0.050735
	19	2	120.00	0.10	9.00	100.00	93.00	Hybrid	0.72	0.165	0.048113
	4	3	120.00	0.10	9.00	80.00	90.00	Seperate	0.91	0.162	0.055592
	6	4	120.00	0.10	9.00	80.00	90.00	Hybrid	0.96	0.155	0.077738
	20	5	90.00	0.10	9.00	100.00	93.00	Seperate	0.65	0.127	0.083561
	31	6	90.00	0.20	2.00	80.00	90.00	Hybrid	0.85	0.124	0.028396
	9	7	90.00	0.20	2.00	100.00	93.00	Hybrid	0.86	0.197	0.028412
	21	8	120.00	0.20	2.00	100.00	90.00	Hybrid	1.04	0.237	0.028182
	14	9	90.00	0.10	2.00	80.00	90.00	Seperate	0.95	0.176	0.079632
	22	10	90.00	0.20	9.00	80.00	90.00	Seperate	1.56	0.113	0.042767
	8	11	90.00	0.10	2.00	100.00	93.00	Seperate	0.74	0.143	0.078327
	32	12	90.00	0.10	2.00	80.00	93.00	Hybrid	0.91	0.145	0.047405
	11	13	120.00	0.20	9.00	100.00	90.00	Seperate	0.83	0.224	0.046309
	26	14	120.00	0.20	2.00	80.00	90.00	Seperate	1.54	0.246	0.043601
	5	15	120.00	0.10	2.00	100.00	93.00	Hybrid	0.66	0.167	0.050219
	3	16	120.00	0.10	2.00	100.00	90.00	Seperate	0.68	0.16	0.074579
	12	17	90.00	0.20	2.00	100.00	90.00	Seperate	0.7	0.165	0.042936
	10	18	120.00	0.20	9.00	80.00	90.00	Hybrid	1.57	0.197	0.024214
	16	19	120.00	0.10	2.00	80.00	90.00	Hybrid	0.75	0.153	0.040502
	28	20	120.00	0.20	9.00	100.00	93.00	Seperate	0.64	0.155	0.078966
	18	21	90.00	0.20	9.00	80.00	93.00	Hybrid	1.13	0.2	0.029083
	24	22	90.00	0.10	9.00	100.00	90.00	Hybrid	1.15	0.191	0.030247
	27	23	90.00	0.10	2.00	100.00	90.00	Hybrid	1.42	0.127	0.04167
	15	24	120.00	0.20	9.00	80.00	93.00	Seperate	0.89	0.225	0.054218
	25	25	90.00	0.20	9.00	100.00	93.00	Seperate	0.91	0.154	0.046697
	13	26	90.00	0.20	2.00	80.00	93.00	Seperate	1.23	0.176	0.050837
	17	27	120.00	0.20	2.00	100.00	93.00	Seperate	0.98	0.235	0.048513
	30	28	120.00	0.20	9.00	100.00	93.00	Hybrid	0.97	0.239	0.025511
	7	29	90.00	0.10	9.00	80.00	93.00	Seperate	0.95	0.167	0.083098
	1	30	90.00	0.10	9.00	100.00	93.00	Hybrid	0.65	0.143	0.047081
	29	31	120.00	0.20	2.00	80.00	93.00	Hybrid	1.08	0.187	0.029913
	23	32	120.00	0.10	2.00	80.00	93.00	Seperate	0.77	0.173	0.084108

Fig. 10 Measured Values DX8 screen shot.

The performance of ANOVA resulted in mathematical models for prediction of tool wear, surface roughness and energy consumption in coded factors (See Appendix-B). Separate un-coded models were also developed for the conventional and hybrid settings. It turned out that for roughness the two most significant parameters were feed and type of grinding wheel. For tool wear the feed and cutting speed and for energy consumption feed and machining technique were significant parameters. The lubrication technique was also significant for surface roughness and tool wear. The predicted values of the models matched the measured value to a fair extent where the maximum deviation (18 percent) occurred in only one case with the rest averaging 10 percent. The models can thus be optimized for each single output response. However, a combined optimized setting with maximum desirability for all responses is shown in Fig. 11.

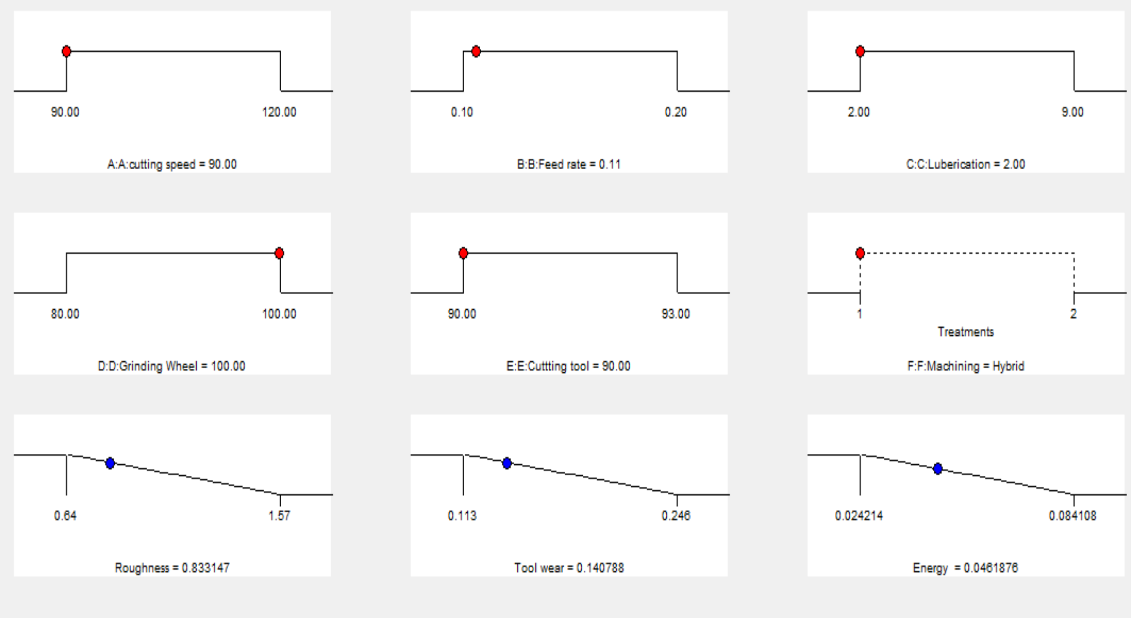


Fig. 11 Optimized setting of cutting speed, feed rate, wheel type, insert type and lubrication and machining strategies achieved using DX8 optimizer giving best surface roughness, tool wear and energy consumption.

The first six blocks on the top represent the input factors with their low and high levels, on the left and right respectively, of the elevated line in each block. The red pointers show the recommended optimized value of that factor. So, the optimized cutting speed is 90 m/min, feed is 0.1mm/rev and controlled lubrication of 2liter/min with grinding wheel of higher grit size. The recommended cutting tool is the uncoated carbide insert and the strategy for machining is hybrid. The lower three blocks represent the resulting output responses and the blue pointers to the left in each block show that all are at their low, optimized values. Hence the study confirms hybrid machining, along with controlled lubrication at a much lower flow rate instead of flood, as a viable machining strategy for sustainable output in terms of minimized tool wear, surface roughness and energy consumption. More on the details of this particular case study and prospective research for hybrid machining as a sustainable strategy will be discussed elsewhere.

4.2.3 Using the Sustainability Calculator

The evaluation of the grinding process in both strategies using the calculator would require a lot of input details and thus become quite user-"unfriendly'. Also, this being a pilot study, not a lot of machinability details has been accommodated in the calculator like tool type, tool wear, surface roughness and grit size. Thus for practical reasons and stand-alone assessment, only the turning process was rated by the calculator. The feature of interest in focus for the calculator is the material removal rate (MRR). Hence, the grinding wheel, tool type and machining strategy parameters are struck out and the following out of our previously conducted DoE are extracted as shown in Table 5.

Table 5 Extracted data sets of parameter settings from DOE.

S/No.	Speed (m/min)	Feed (mm/rev)	Lubrication (Litre/min)
1	120	0.1	9
2	90	0.1	9
3	90	0.1	2
4	120	0.2	2
5	120	0.1	2
6	90	0.2	2
7	120	0.2	9
8	90	0.2	9

After this, all the parameter setting blocks were input into the calculator. The process type was selected to turning. A simplistic G-code file for the given tool-path was also uploaded into the calculator so that the dry-run energy could also be calculated using the motor-ratings of the machine. Thus the energy consumption is calculated in three sections,

$$E_{consumed} = E_{idle\ power} + E_{dry\ run} + E_{\ cut} \tag{1}$$

Given below are some basic formulas used for turning scenarios [59],

$$MRR = V \times f_R \times d \tag{2}$$

$$T_m = \frac{L}{f_m} \tag{3}$$

Following is the basic equation used to calculate the sustainability indices,

$$XSI = \frac{Environmental\ Burden}{MRR} \times Scaling\ Factor \tag{4}$$

For the process at hand the four settings with a cutting speed of 120 m/min or 90 m/min and feed rate of 0.1 mm/rev gave energy consumption values close to 0.03 kWh, while the other four settings with a feed rate of 0.2 mm/rev returned energy consumption values close to 0.02 kWh.

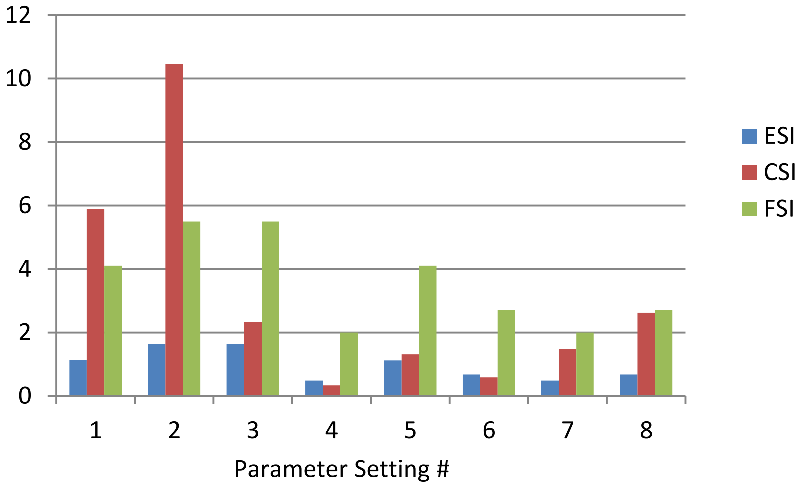


Fig. 12 Sustainability indicators for all parameter settings.

As mentioned before, the resulting energy and coolant consumption were converted into their corresponding environmental burdens. These values, along with the cost of machining, were then divided by the process MRR and scaled to make them presentable in terms of position of the decimal point. These values are now comparable with not only themselves, but with values resulting from another processes, e.g. milling. The results of the calculator were also fairly close to these measured values. The less or more value of coolant consumption didn’t have much effect on energy. But it has a significant effect on environmental burden. After conversion of these quantities the lowest value for all indices were at setting#4 with an MRR of 9600 mm^3/min when ESI=0.4771, for CSI=0.3271 and FSI=2.0 thus resulting in the most sustainable of all eight settings in terms of cost, environmental burden and production rate, all together. It can be seen in Fig.12 that parameter setting 2 and 3 both have the same FSI; however, the CSI value of setting 2 is much higher than 3. Thus the rating system identifies the more sustainable setting, which is 3, even when the cost effectiveness of the two processes is the same. It is visible that although the tooling costs were same for each process and single part production yielded very small energy consumption costs, the FSI still had an important role in the decision making process.

Now the concept of Chapter 2 is applied in Fig.13 where the inverse values of the same data points in Fig.12 are plotted. Now it can be seen that the same results are obtained, i.e. setting no.4 is still the most sustainable. However, the presentation is clearer than before. Hence the higher the value of an index, the better it is.

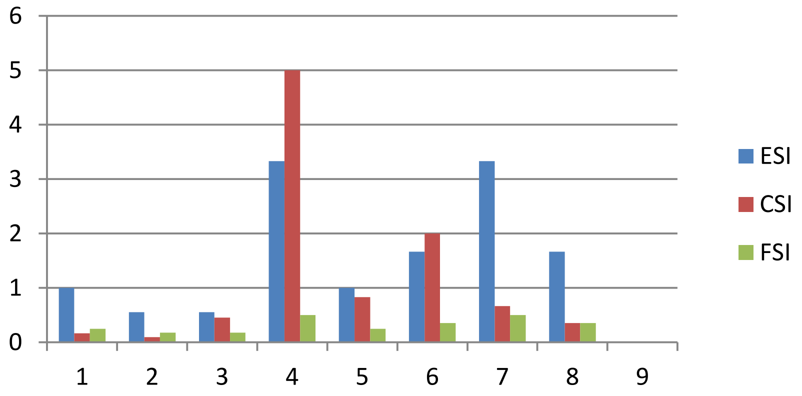


Figure 13 'The higher the better' approach.

Hence a more elaborate way of interpreting the phenomenon of sustainability was proposed. Using the proposed approach a set of practical cases of machining were studied and the resulting set of indices provided an all-inclusive evaluation of process sustainability. A clear breakdown of energy consumption was presented based on actual tool path evaluation. It is important to note that the idea of utilizing the ‘feature of interest’ can be extended to other outputs of the machining process like surface quality, tool life and wear. If a decreasing feature of interest is desirable, e.g. tool wear, then the high values of indices represent the best results. Moreover, if the design space for parameter selection and/or the desired ‘level’ of sustainability is known, then the sustainability indices and the feature of interest can themselves be normalized for even clearer representation of the system. It is important to note that the lubrication for machining turns out to be a very important parameter. This can be seen not only from the ANOVA results, but also from the CSI value of the parameter settings under study. The importance of the lubrication technique becomes even more evident if the cost of lubrication is taken into account. Therefore, it appears advisable to further investigate various lubrication techniques and evaluate their effect on process sustainability. More research and validation through case studies can follow, with more precise energy and cost measurement models and techniques, to realize the goal of easy and practical sustainability assessment of machining processes. Fig.14 shows a power consumption graph obtained using PSM.

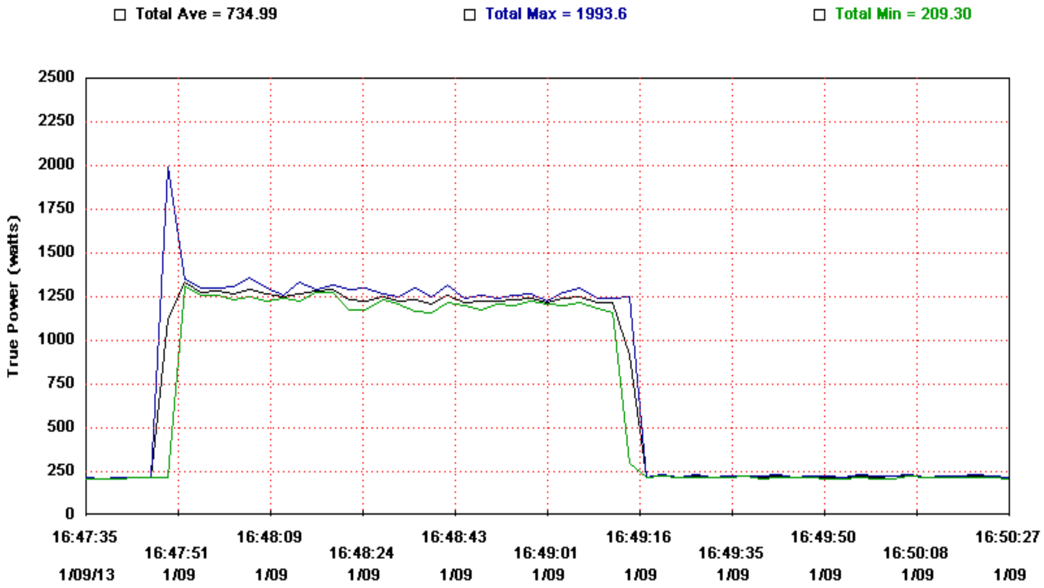


Fig. 14 PowerSight Manager Graph for a run.

4.3 Comparison of environmentally benign cooling strategies

This case study is an extension of the previous study with necessary amendments. Establishing the need of focus and leaving out the extra details, we now shall be more interested in the lubrication techniques while using a specific cutting tool insert and feed and speed levels. Our prime interest, like before, is to evaluate the techniques which are dubbed ‘sustainable’, like the vegetable oil lubrication, in terms of their performance against surface roughness, tool wear and power consumption.

4.3.1 Design of Experiments and Experimental Setup

Again, the Design Expert (8.0.7.1) package was utilized to carry out the design of the experiments. A total of 72 randomized runs were designed with a variation of parameters. These runs include three blocks for replicating the results of the actual set of 24 runs for satisfaction and surety in the results (Table.6). The six cooling strategies were analyzed against a mix of the Hi and Lo levels of cutting speed and feed, which have been selected close to the prevalent machine settings[58]. Fig.15 shows the DOE framework.

The results section includes the measuring of flank tool wear (Vb) and average surface roughness (Ra) along with the energy consumption of the process. The power consumption would be recorded by using PowerSight Manager (PSM) to be later on converted into energy consumption.

The flood cooling is provided using an external setup for pumping with a flow-rate of 9 liter/min. For the administration of the MQL and MQCL using vegetable oil, a stand-alone booster system is installed on the machine tool. A nominal oil flow rate of 2.8 ml/min is to be supplied by the booster pump. The vegetable oil used by this setup is ECOLUBRIC E200, a cold-pressed rapeseed oil type without additives. Manufactured according to the Swedish National Food Administration regulations, it consists of biodegradable substances and is deemed fit for industrial use. The oil is declared environmentally harmless and has a biodegradability of 90% in 28 days [60]. Figures 16 and 17 show the photographic and schematic illustrations of the experimental set up respectively.

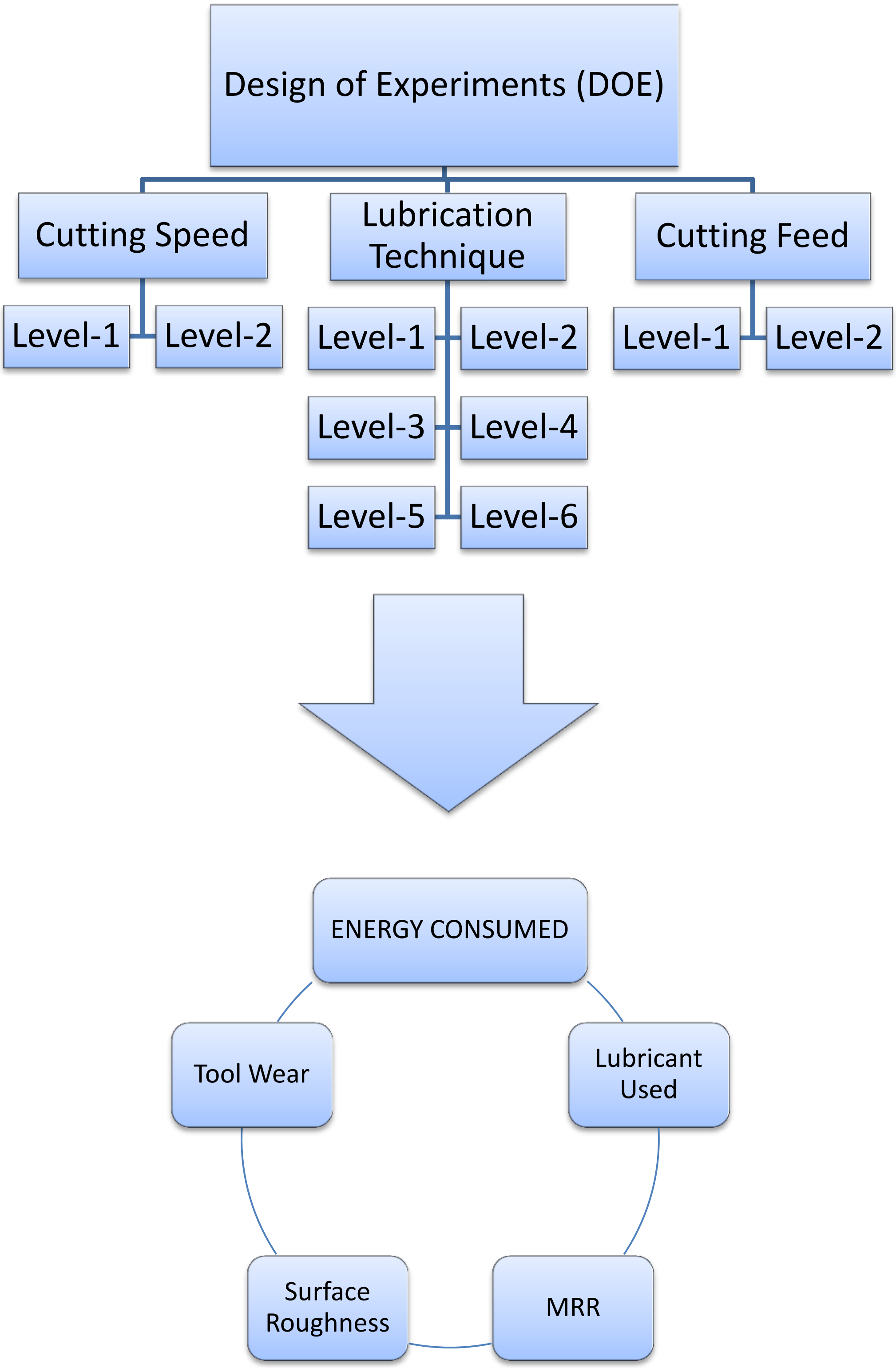


Fig. 15 Design of Experiments Framework.

Table 6 Design of Experiments-II

Std	Run	Block #	Feed (mm/rev)	Cutting Speed (m/s)	Lubrication Technique
22	1	Block 1	0.2	120	Dry
49	2	Block 1	0.1	90	Veg. Oil MQL
28	3	Block 1	0.2	90	MQL
67	4	Block 1	0.1	120	MQCL Veg. Oil
31	5	Block 1	0.1	120	MQL
19	6	Block 1	0.1	120	Dry
34	7	Block 1	0.2	120	MQL
70	8	Block 1	0.2	120	MQCL Veg. Oil
55	9	Block 1	0.1	120	Veg. Oil MQL
13	10	Block 1	0.1	90	Dry
64	11	Block 1	0.2	90	MQCL Veg. Oil
40	12	Block 1	0.2	90	Cooled Air
46	13	Block 1	0.2	120	Cooled Air
52	14	Block 1	0.2	90	Veg. Oil MQL
61	15	Block 1	0.1	90	MQCL Veg. Oil
43	16	Block 1	0.1	120	Cooled Air
25	17	Block 1	0.1	90	MQL
16	18	Block 1	0.2	90	Dry
4	19	Block 1	0.2	90	Flood
1	20	Block 1	0.1	90	Flood
10	21	Block 1	0.2	120	Flood
58	22	Block 1	0.2	120	Veg. Oil MQL
37	23	Block 1	0.1	90	Cooled Air
7	24	Block 1	0.1	120	Flood
26	25	Block 2	0.1	90	MQL
68	26	Block 2	0.1	120	MQCL Veg. Oil
38	27	Block 2	0.1	90	Cooled Air
32	28	Block 2	0.1	120	MQL
47	29	Block 2	0.2	120	Cooled Air
35	30	Block 2	0.2	120	MQL
44	31	Block 2	0.1	120	Cooled Air
8	32	Block 2	0.1	120	Flood
11	33	Block 2	0.2	120	Flood
2	34	Block 2	0.1	90	Flood
50	35	Block 2	0.1	90	Veg. Oil MQL
14	36	Block 2	0.1	90	Dry
29	37	Block 2	0.2	90	MQL
20	38	Block 2	0.1	120	Dry
59	39	Block 2	0.2	120	Veg. Oil MQL
62	40	Block 2	0.1	90	MQCL Veg. Oil

56	41	Block 2	0.1	120	Veg. Oil MQL
5	42	Block 2	0.2	90	Flood
41	43	Block 2	0.2	90	Cooled Air
23	44	Block 2	0.2	120	Dry
17	45	Block 2	0.2	90	Dry
53	46	Block 2	0.2	90	Veg. Oil MQL
71	47	Block 2	0.2	120	MQCL Veg. Oil
65	48	Block 2	0.2	90	MQCL Veg. Oil
36	49	Block 3	0.2	120	MQL
21	50	Block 3	0.1	120	Dry
42	51	Block 3	0.2	90	Cooled Air
15	52	Block 3	0.1	90	Dry
60	53	Block 3	0.2	120	Veg. Oil MQL
12	54	Block 3	0.2	120	Flood
63	55	Block 3	0.1	90	MQCL Veg. Oil
66	56	Block 3	0.2	90	MQCL Veg. Oil
18	57	Block 3	0.2	90	Dry
3	58	Block 3	0.1	90	Flood
9	59	Block 3	0.1	120	Flood
51	60	Block 3	0.1	90	Veg. Oil MQL
39	61	Block 3	0.1	90	Cooled Air
30	62	Block 3	0.2	90	MQL
72	63	Block 3	0.2	120	MQCL Veg. Oil
24	64	Block 3	0.2	120	Dry
27	65	Block 3	0.1	90	MQL
57	66	Block 3	0.1	120	Veg. Oil MQL
54	67	Block 3	0.2	90	Veg. Oil MQL
6	68	Block 3	0.2	90	Flood
45	69	Block 3	0.1	120	Cooled Air
33	70	Block 3	0.1	120	MQL
48	71	Block 3	0.2	120	Cooled Air
69	72	Block 3	0.1	120	MQCL Veg. Oil

Fig. 16 Eco-Lubric Booster system.

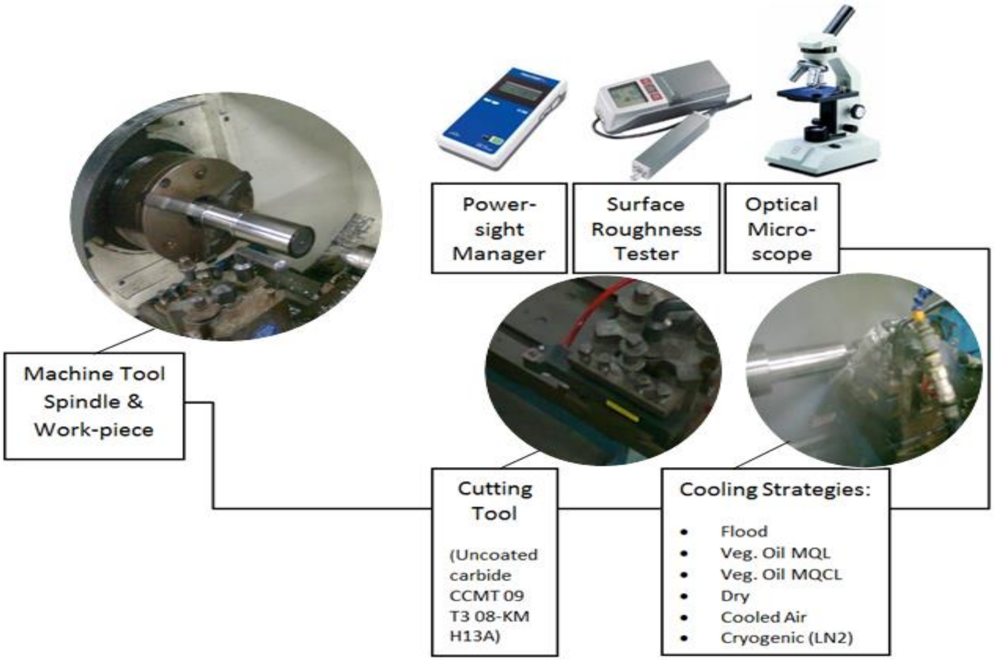


Fig. 17 Schematic diagram of experimental setup.

4.3.2 Results and Analysis:

After conducting all the 72 runs, an overall presentation of the replicated results is given in Table 7 below.

Table 7 Measured values against replicated runs

Cutting Feed (mm/rev)	Cutting Speed (m/min)	Lubrication Tech.	Tool Wear V_b (mm)	Surface Roughness Ra (μm)	Energy Consumed (kWh)
0.1	90	Dry	0.126	0.893	0.0288
0.1	90	Veg. Oil MQL	0.101	0.91	0.0181
0.1	90	MQCL Veg. Oil	0.088	0.846	0.0298
0.1	90	Cooled Air	0.119	0.823	0.0306
0.1	90	Flood	0.104	0.833	0.0286
0.1	90	Cryogenic	0.088	1.413	0.0287
0.2	90	Dry	0.156	2.33	0.0174
0.2	90	Veg. Oil MQL	0.1623	2.253	0.0108
0.2	90	MQCL Veg. Oil	0.152	2.206	0.0175
0.2	90	Cooled Air	0.154	2.123	0.0177
0.2	90	Flood	0.118	2.286	0.0173
0.2	90	Cryogenic	0.129	1.776	0.0154
0.1	120	Dry	0.163	0.903	0.0308
0.1	120	Veg. Oil MQL	0.174	0.976	0.0123
0.1	120	MQCL Veg. Oil	0.1625	0.87	0.0246
0.1	120	Cooled Air	0.135	0.943	0.0231
0.1	120	Flood	0.119	0.753	0.0305
0.1	120	Cryogenic	0.120	0.976	0.0178
0.2	120	Dry	0.605	1.513	0.0191
0.2	120	Veg. Oil MQL	0.525	1.486	0.0081
0.2	120	MQCL Veg. Oil	0.359	1.92	0.0116
0.2	120	Cooled Air	0.402	1.605	0.0119
0.2	120	Flood	0.250	2.123	0.0182
0.2	120	Cryogenic	0.227	1.913	0.0114

It must be noted here that the number of digits after the decimal is a result of taking the average of the replicate blocks.

Tool Wear

When each parameter setting comprising of high and/or low levels of cutting speed and feed are plotted versus the lubrication techniques, the effects on the tool wear can be seen. A closer look at each setting tells us that at low speed and feed, which is the representative setting with the insert and the study at hand, the best performance in terms of lowest flank wear of the tool is given by the MQCL with vegetable oil. Fig.18 shows this behavior.

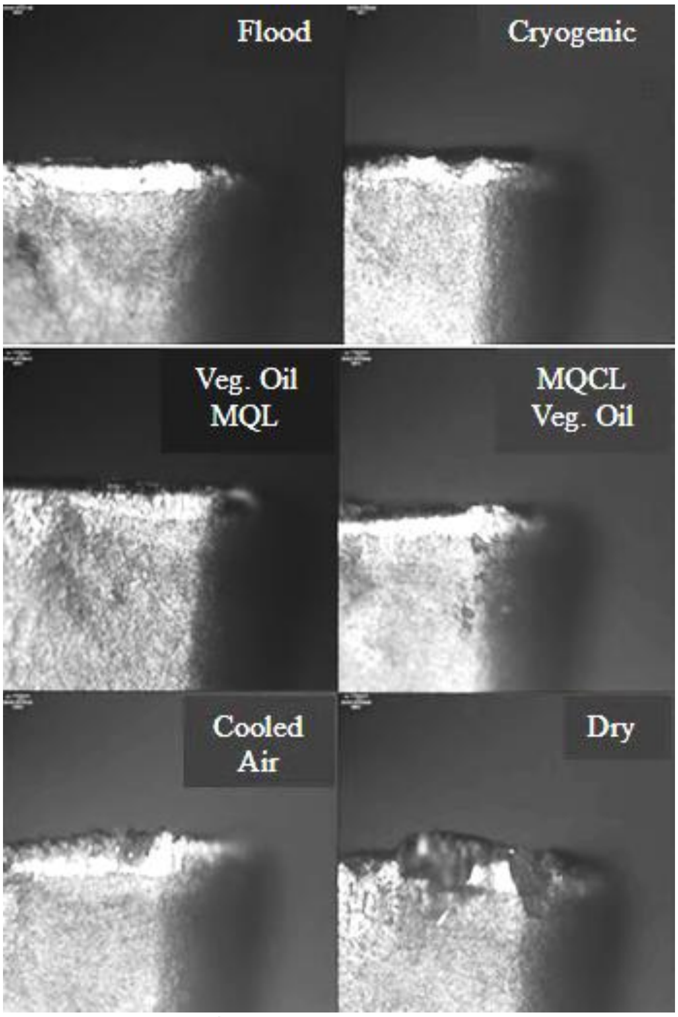


Fig. 18 Flank tool wear at feed=0.1 mm/rev and speed = 90 m/min using optical microscope

It was seen that while the flood cooling technique using a synthetic coolant yielded the least tool wear overall, cryogenic machining was the second best and MQCL also offered less tool wear. The use of cooled air emerges as a better alternative against dry machining and so does MQCL with vegetable oil against MQL using the same. This is true even though the cooled air used in this setup is not as cold and compressed as conventional air cooling systems for machining; plus the importance of nozzle configuration cannot be neglected in this regard [28], [41], [61]. Another observation is that unless the speed and feed are both at their Hi levels, the tool wear for all techniques remains below or close to 0.3mm [62]. However the surge in the resulting tool wear at the high-feed-high-speed combination suggests that perhaps this combination is not appropriate for titanium machining using an uncoated carbide tool. This applies to cases of techniques other than flood and cryogenic strategies and MQCL to some extent. Fig. 19 is a bar chart showings these effects

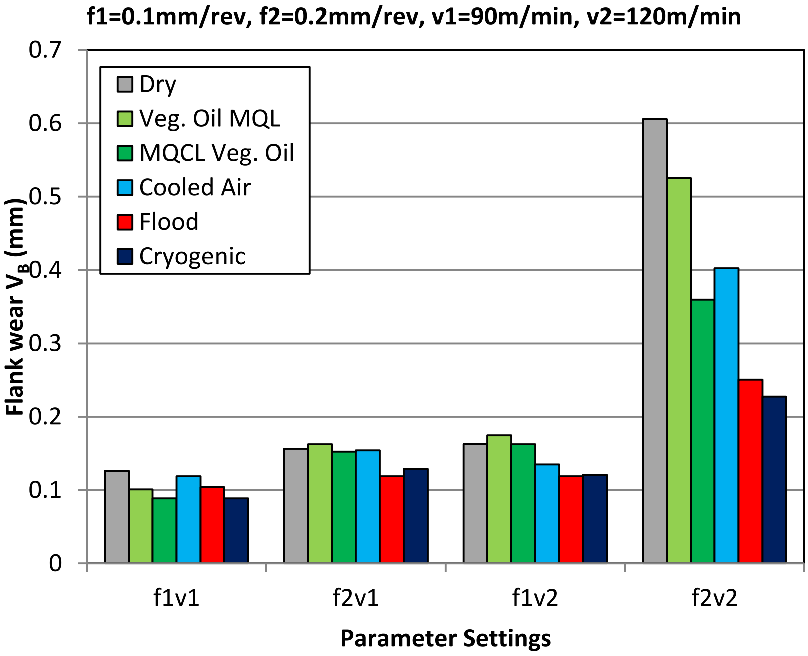


Fig. 19 Tool Wear with lubrication techniques.

Surface Roughness

The effect of changing parameters on the surface roughness using various lubrication techniques can be seen in Fig. 20. It can be seen that at low feeds the surface roughness is much less and increases slightly upon using higher speed for the same feed. Flood cooling appears to be the lubrication of choice when using low feed but not for high feed, with cryogenic machining giving slightly better results. At high speed, however, the use of cooled air as the lubricant emerges as the better alternative. However, at low speed, it does not yield good surface finish [63]. It is also visible that in low feed cases, the surface roughness achieved through all techniques is close to each other, a trend not found at the high feed. Moreover, an important point to note is the promise shown by both MQL and MQCL using vegetable oil overall. Referring back to Fig. 19, it was seen that the high-feed-high-speed setting yielded very high tool wears (above 0.4 mm) compared to other settings in some strategies. This high wear is responsible for generating a smoother surface than the high-feed-low-speed case while incorporating dimensional inaccuracy, which means the material removed is reduced, as the turning progressed.

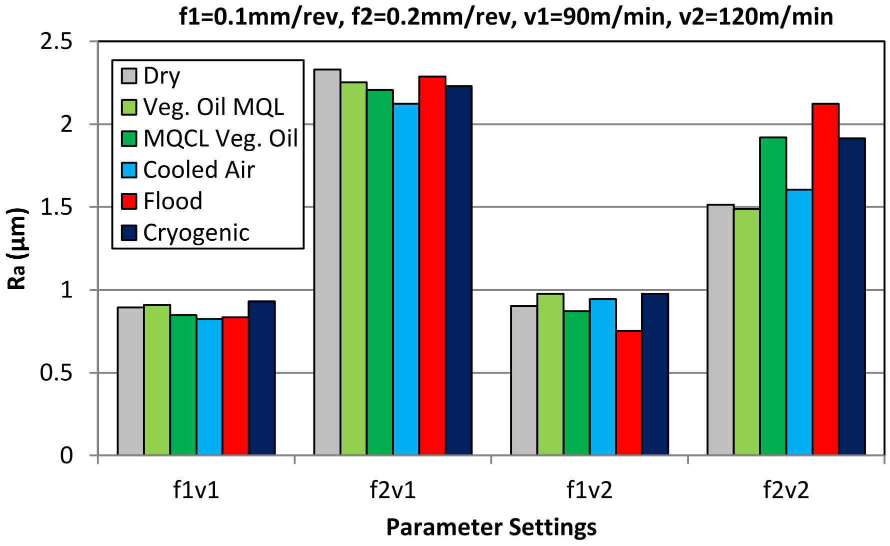


Fig. 20 Surface Roughness with Lubrication Techniques

Effect on Energy Consumption

The plot showing the effect of various lubrication techniques on cutting energy consumption at various parameter settings is given in Fig. 21. It is clearly visible that the MQL using vegetable oil provides the best lubrication and thus yields lesser energy consumption for cutting. Vegetable oil MQCL also shows good results overall again due to the good lubricity provided by it. Also, cryogenic machining closely follows this trend except at the low feed and speed case. However, cooled air performs better than flood and dry machining overall with dry machining as the least suitable alternative. It is also observable that the cutting energy consumption increases with a decrease in feed.

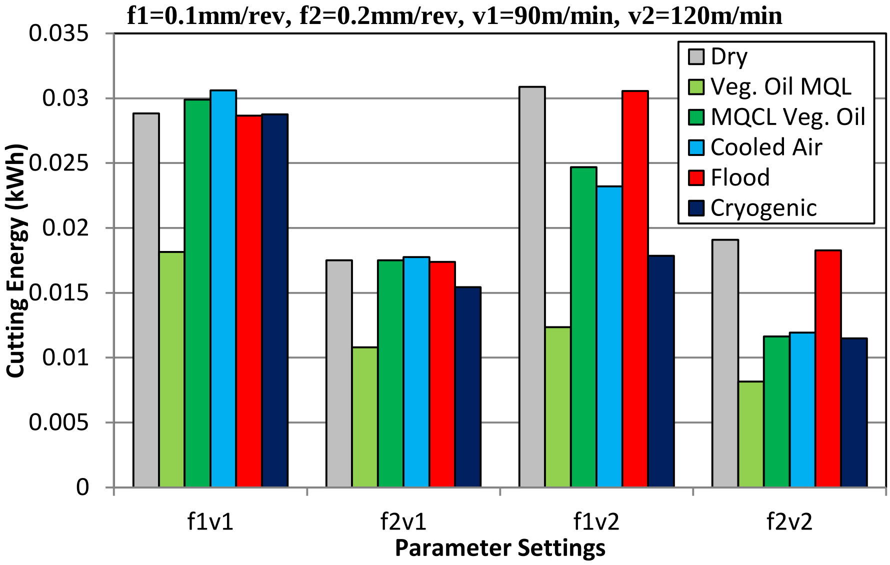
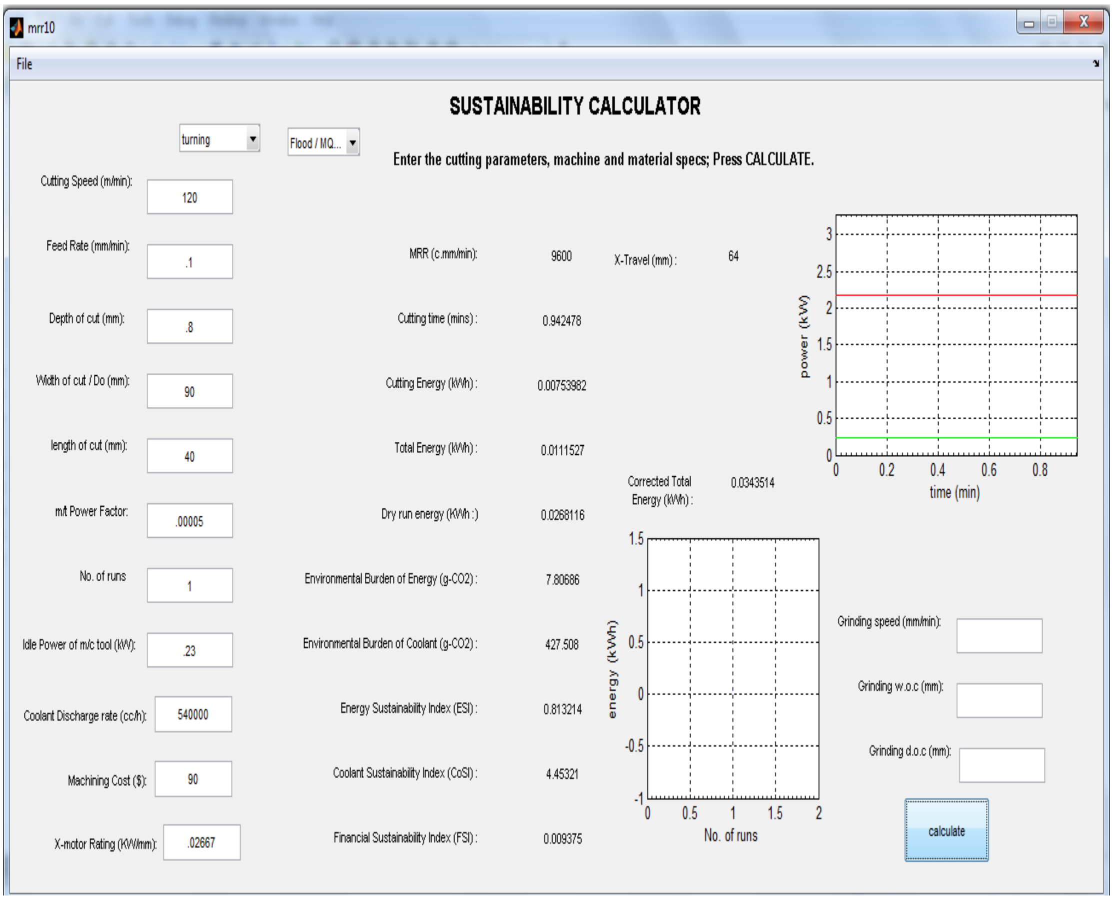


Fig. 21 Cutting Energy Consumption with Lubrication Techniques.

Looking at Figures 18, 19, 20 and 21 together tells about the overall performance of the lubrication techniques. It can be seen that the vegetable oil MQL and MQCL techniques provide promising results in terms of tool wear and surface roughness and supersede the others in terms of cutting energy consumption as well. Owing to the efficient coolant delivery and good lubricity offered in these techniques, sustainable results like better quality of surface, less tool wear and less energy consumption are yielded. Especially, at lower feeds and speeds, the MQCL of vegetable oil is very promising, thus confirming that the use of vegetable oil in machining is a sustainable practice in comparison with others. Also, the smaller wattage of the booster pump for ECOLUBRIK is another advantage against the normally prevalent flood cooling technique using a heavier pump. The results also show the high effectiveness of cryogenic machining using liquid nitrogen as a highly recommendable alternative at all the levels. However, the high cost associated with the supply of the liquid nitrogen cooling system in comparison with the vegetable oil booster system still remains an issue. The tradeoff appears to be in the cooling temperature where the small booster system cannot provide temperatures as low as in cryogenic or conventional low temperature air-cooling systems for machining.

4.3.3 Using the Sustainability Calculator

Following the methodology involved in first set of experiments, another set of sample runs (Table 8) was separated for analysis using the sustainability calculator. New modifications were made to account for the lubrication techniques as shown in Fig. 22. The analysis of the second study data is discussed further. This time the values of the sustainability indices received from the calculator were scaled and adjusted to round numbers. This time again, it was easy to select the most suitable parameter setting by looking at the plot in Fig. 23.



SUSTAINABILITY CALCULATOR

turning

Flood / MQ...

Enter the cutting parameters, machine and material specs; Press CALCULATE.

Cutting Speed (m/min): 120

Feed Rate (mm/min): .1

Depth of cut (mm): .8

Width of cut / Do (mm): 90

length of cut (mm): 40

m/t Power Factor: .00005

No. of runs 1

Idle Power of m/c tool (kW): .23

Coolant Discharge rate (cc/h): 540000

Machining Cost ($): 90

X-motor Rating (KW/mm): .02667

MRR (c.mm/min): 9600

X-Travel (mm) : 64

Cutting time (mins) : 0.942478

Cutting Energy (kWh) : 0.00753982

Total Energy (kWh) : 0.0111527

Corrected Total Energy (kWh) : 0.0343514

Dry run energy (KWh :) 0.0268116

Environmental Burden of Energy (g-CO2) : 7.80686

Environmental Burden of Coolant (g-CO2) : 427.508

Energy Sustainability Index (ESI) : 0.813214

Coolant Sustainability Index (CoSI) : 4.45321

Financial Sustainability Index (FSI) : 0.009375

Grinding speed (mm/min):

Grinding w.o.c (mm):

Grinding d.o.c (mm):

Fig. 22 Revised Calculator Interface

Table 8 Test Matrix-II (Randomized)

S/No.	Speed (m/min)	Feed (mm/rev)	Lubrication	ESI	CSI	FSI
1	0.1	120	MQCL Veg. Oil	8	0	5
2	0.2	120	MQCL Veg. Oil	3	0	3
3	0.2	90	MQCL Veg. Oil	5	0	3
4	0.1	90	MQCL Veg. Oil	12	0	7
5	0.2	90	Flood	4	2	3
6	0.1	90	Flood	11	7	7
7	0.2	120	Flood	3	1	3
8	0.1	120	Flood	7	4	5

In this study the MQCL and MQL use vegetable oil ECOLUBRIK E200L which is a cold pressed rapeseed oil without additives. Since vegetable oil is supposed to be an environmentally-friendly lubricant [31], its environmental burden is taken as zero. The same is the case with cooled air, etc. By looking at the plot in Fig.23, it can be seen that not only is it environmentally sustainable but the related financial and energy sustainability indices for using MQCL with vegetable oil are promising. In fact, the most sustainable is the parameter set #2 which shows the lowest amount of sustainability indices.

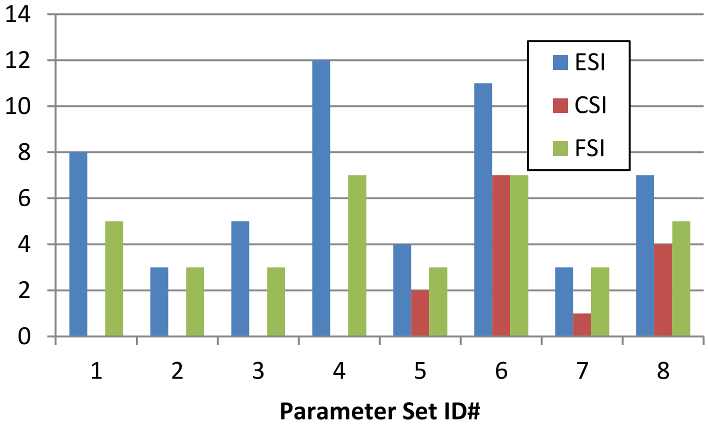


Fig. 23 Sustainability Indices plot

The plot shown in Fig. 23 is based on a "the lower the better approach". The approach discussed earlier in Chapter 2 is utilized in Fig. 24. Similar to the material indices development method [49], [50], the indices values are inversed in Fig. 23 so that the highest value of the index indicates the best scenario. It must be noted that the results measured are the same, only the values of the indices change. This representation, while giving the same conclusion, makes it even easier to interpret the plot. Moreover, it must be noted that since inversing an environmental burden of zero gCO_2/cc of coolant would yield an 'NaN' error in MATLAB, an arbitrarily small environmental burden of 1 gCO_2/cc is allocated to vegetable oil lubrication.

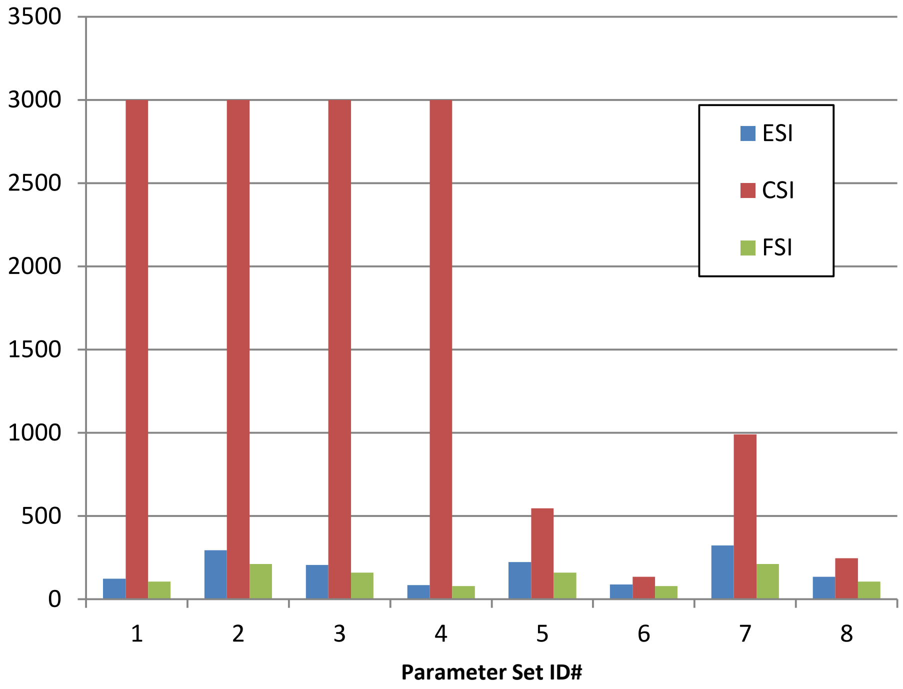


Fig. 24 Sustainability Indices plot

It is visible that again, the most feasible parameter setting is set #2 with competitively close ESI and FSI along with a very high CSI. It is also important to note that, for the sake of visibility, the very high values for the vegetable oil lubrication with extremely low environmental burden were trimmed to 3000, so that all indices could be viewed and compared on the same graph.

6. Summary & Conclusions

The need for a more elaborate way of interpreting the phenomenon of sustainability was identified and a new approach of sustainability indices was proposed. Using the proposed approach a set of practical cases of machining was studied and the resulting set of indices provided an all-inclusive evaluation of process sustainability. A clear breakdown of energy consumption was presented based on actual tool path evaluation. It is important to note that the idea of utilizing the ‘feature of interest’ can be extended to other outputs of the machining process like surface quality, tool life and wear, etc. If a decreasing feature of interest is desirable, e.g. tool wear, then the high values of indices represent the best results. Moreover, if the design space for parameter selection and/or the desired ‘level’ of sustainability is known, then the sustainability indices and the features of interest can themselves be normalized for even clearer representation of the system. Thus more research and validation through case studies can follow, with more precise energy and cost measurement, to realize the goal of easy and practical sustainability assessment of machining processes.

The sustainability calculator thus developed proved useful in providing insight for the parameter selection process. Various details were added to the interface to make it more and more flexible for handling various machining scenarios. More effort in this area can still result in better process assessment. It is important to note that in the case studies presented, the use of the calculator was for putting forth the idea of such an interface and to present the concept of using our proposed sustainability indices as one way of sustainability assessment. Hence a better representation of machining costs, environmental burdens for sustainable lubrication and dry run power consumption will improve the working of the calculator.

The sustainability of various techniques and practices dubbed as sustainable practices was assessed both by sustainability indices and conventional performance in terms of tool wear, surface roughness, etc. The exercise involved a detailed case study of evaluating hybrid turning/grinding with sequential turning and grinding along with a comparison between controlled and flood lubrication using ANOVA. It was confirmed that hybrid machining and controlled lubrication are indeed sustainable alternatives. The second set of experiments involved analysis of various lubrication techniques. The often proposed use of vegetable oil as a machining lubricant was tested in titanium turning. Again, it was concluded that it really is a more sustainable alternative to synthetic cooling in terms of tool wear, surface quality and cutting energy consumed, combined. Also the booster pumps required for the small flow of vegetable oil and air mixtures are much lighter than the pumping system required for the flood cooling technique. Although the flood cooling technique is the more prevalent practice in the industry these days, this study shows that it is feasible to use the sustainable alternative of vegetable oil, especially at feeds and speeds close to 0.1 mm/min and 90 m/min, respectively, for titanium. This means it would be sustainable by default for softer metals and alloys. The application of cooled air as a lubricant also appeared to be effective as presented in the literature. Especially when compared with dry machining, it turns out to be a good alternative. Moreover, following the trends shown in literature, cryogenic machining also turned out to be a recommendable alternative by outperforming flood cooling at the overall three levels, even at higher feeds and speeds. Although in cutting energy consumption its performance was inferior to vegetable oil, this was compensated to some extent by the low tool wear achieved at higher feeds and speeds.

6.1 Future Work

A newer version of the sustainability calculator will be developed with the ability to take into account a more detailed cost model and more machinability aspects. The cost-to-effectiveness extent needs to be further investigated between cryogenic and vegetable oil booster systems. It would, however, be appropriate to further execute this study using a coated carbide grade because, while the aim was to push for challenging machining scenarios, the higher speed selected might be a little more than an uncoated tool can deal with. Hence, further studies, perhaps with detailed LCA can follow with more detail and a wider range of parameters. The development of a mathematical model in this regard will also be a promising contribution for titanium machining.

7. References

[1] I. T. A. U.S. Department of Commerce, “How Does Commerce Define Sustainable Manufacturing? .,” 2007. [Online]. Available: http://trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp. [Accessed: 21-Sep-2012].

[2] S. Bell and S. Morse, *Sustainability indicators: measuring the immeasurable*. London: Earthscan, 1999, p. xiv,175.

[3] Z. Bi, “Revisiting System Paradigms from the Viewpoint of Manufacturing Sustainability,” *Sustainability*, vol. 3, no. 9, pp. 1323–1340, Aug. 2011.

[4] D. Dornfeld, “Opportunities and Challenges to Sustainable Manufacturing and CMP,” in *MRS Spring Meeting, San Francisco, April 14-16*, 2009.

[5] F. Jovane, Y. Koren, and C. R. Boër, “Present and Future of Flexible Automation: Towards New Paradigms,” *CIRP Ann. - Manuf. Technol.*, vol. 52, no. 2, pp. 543–560, Jan. 2003.

[6] M. Mani, K. Lyons, and S. Rachuri, “Introducing Sustainability Early Into Manufacturing Process Planning,” in *14th International Conference on Manufacturing Science and Engineering October 7-10, 2008, Evanston, IL, USA*, 2008, pp. 1–8.

[7] F. Pusavec and J. Kopac, “Achieving and implementation of sustainability principles in machining processes,” *J. Adv. Prod. Eng. Manag.*, vol. 3, pp. 58–69, 2009.

[8] J. Dreher, M. Lawler, J. Stewart, G. Strasorier, and M. Thorne, “Metrics for Sustainable Manufacturing. 15.992 – Strategies for Sustainable Business Sustainability Metrics for General Motors,” 2009.

[9] N. Diaz, M. Helu, and S. Jayanathan, “Environmental analysis of milling machine tool use in various manufacturing environments,” in *IEEE International Symposium on Sustainable Systems and Technology (ISSST) .*, 2010, pp. 1–6.

[10] S. Feng and C. Joung, “An overview of a proposed measurement infrastructure for sustainable manufacturing,” in *Proceedings of the 7th Global Conference on Sustainable Manufacturing.*, 2009, pp. 355–360.

[11] A. D. Jayal, F. Badurdeen, O. W. Dillon, and I. S. Jawahir, “Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels,” *CIRP J. Manuf. Sci. Technol.*, vol. 2, no. 3, pp. 144–152, Jan. 2010.

[12] W. Schmidt and A. Taylor, “Ford of Europe’s Product Sustainability Index,” in *Proceedings of 13th CIRP International Conference on Life Cycle Engineering.*, 2006, pp. 5–10.

[13] H. Narita, N. Desmira, and H. Fujimoto, “Environmental burden analysis for machining operation using LCA method,” in *Manufacturing Systems and Technologies for the New Frontier.*, 2008, pp. 65–68.

[14] M. F. Rajemi, P. T. Mativenga, and a. Aramcharoen, “Sustainable machining: selection of optimum turning conditions based on minimum energy considerations,” *J. Clean. Prod.*, vol. 18, no. 10–11, pp. 1059–1065, Jul. 2010.

[15] F. Pusavec, P. Krajnik, and J. Kopac, “Transitioning to sustainable production – Part I: application on machining technologies,” *J. Clean. Prod.*, vol. 18, no. 2, pp. 174–184, Jan. 2010.

[16] F. Pusavec, D. Kramar, P. Krajnik, and J. Kopac, “Transitioning to sustainable production – part II: evaluation of sustainable machining technologies,” *J. Clean. Prod.*, vol. 18, no. 12, pp. 1211–1221, Aug. 2010.

[17] T. G. Gutowski, D. P. Sekulic, and B. R. Bakshi, “Preliminary thoughts on the application of thermodynamics to the development of sustainability criteria,” *2009 IEEE Int. Symp. Sustain. Syst. Technol.*, pp. 1–6, May 2009.

[18] T. G. Gutowski, M. S. Branham, J. B. Dahmus, A. J. Jones, and A. Thiriez, “Thermodynamic analysis of resources used in manufacturing processes.,” *Environ. Sci. Technol.*, vol. 43, no. 5, pp. 1584–90, Mar. 2009.

[19] T. Gutowski, J. Dahmus, and A. Thiriez, “Electrical Energy Requirements for Manufacturing Processes,” no. Cvd, 2006.

[20] J. Jeswiet and S. Kara, “Carbon emissions and CES^{TM} in manufacturing,” *CIRP Ann. - Manuf. Technol.*, vol. 57, no. 1, pp. 17–20, Jan. 2008.

[21] J. Fiksel, J. McDaniel, and C. Mendenhall, “Measuring progress towards sustainability principles, process and best practices,” in *Greening of Induatry Network Conference, Best Practice Proceedings*, 1999, vol. 2693, no. 614.

[22] S. Feng, C. Joung, and G. Li, “Development overview of sustainable manufacturing metrics,” in *Proceedings of the 17th CIRP international conference on life cycle engineering.*, 2010, pp. pp. 6–12.

[23] I. Deiab, L. Pang, H. A. Kishawy, and N. A. Al-Kheily, “On A Benign Approach For Machining,” in *Proceedings of The Canadian Society for Mechanical Engineering Forum*, 2010.

[24] S. Feng and M. Hattori, “Cost and Process Information Modeling for Dry Machining,” in *In Proc. of the International Workshop for Environment Conscious Manufacturing-ICEM-2000*, 2000, pp. 1–8.

[25] F. Klocke and G. Eisenblätter, “Dry Cutting,” *CIRP Ann. - Manuf. Technol.*, vol. 46, no. 2, pp. 519–526, 1997.

[26] G. Byrne and E. Scholta, “Environmentally Clean Machining Processes — A Strategic Approach,” *CIRP Ann. - Manuf. Technol.*, vol. 42, no. 1, pp. 471–474, 1993.

[27] a. Shokrani, V. Dhokia, and S. T. Newman, “Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids,” *Int. J. Mach. Tools Manuf.*, vol. 57, pp. 83–101, Jun. 2012.

[28] S. Zhang, J. F. Li, and Y. W. Wang, “Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions,” *J. Clean. Prod.*, vol. 32, pp. 81–87, Sep. 2012.

[29] M. Siniawski and C. Bowman, “Metal working fluids: finding green in the manufacturing process,” *Ind. Lubr. Tribol.*, vol. 61, no. 2, pp. 60–66, 2009.

[30] F. Pušavec and J. Kopač, “Sustainability Assessment: Cryogenic Machining of Inconel 718,” *Strojniški Vestn. – J. Mech. Eng.*, vol. 57, no. 09, pp. 637–647, Sep. 2011.

[31] S. Safian, M. A. Hisyam, and S. Aman, “Evaluation Of Vegetable Oil As An Alternative Cutting Lubricant When End Milling Martensitic Stainless Steel Using Uncoated Carbide Tool,” *J. Adv. Manuf. Technol.*, vol. 3, no. 2, pp. 49–56, 2009.

[32] G. Burton and M. B. G. Jun, “Feasibility of Vegetable Oil in Water Emulsion Achieved through Ultrasonic Atomization as Cutting Fluids,” vol. 40, 2012.

[33] K. A. Venugopal, S. Paul, and A. B. Chattopadhyay, “Tool wear in cryogenic turning of Ti-6Al-4V alloy,” *Cryogenics (Guildf).*, vol. 47, no. 1, pp. 12–18, Jan. 2007.

[34] M. J. Bermingham, S. Palanisamy, D. Kent, and M. S. Dargusch, “A comparison of cryogenic and high pressure emulsion cooling technologies on tool life and chip morphology in Ti–6Al–4V cutting,” *J. Mater. Process. Technol.*, vol. 212, no. 4, pp. 752–765, Apr. 2012.

[35] M. H. Cetin, B. Ozcelik, E. Kuram, and E. Demirbas, “Evaluation of vegetable based cutting fluids with extreme pressure and cutting parameters in turning of AISI 304L by Taguchi method,” *J. Clean. Prod.*, vol. 19, no. 17–18, pp. 2049–2056, Nov. 2011.

[36] D. Fratila and C. Caizar, “Application of Taguchi method to selection of optimal lubrication and cutting conditions in face milling of AlMg3,” *J. Clean. Prod.*, vol. 19, no. 6–7, pp. 640–645, Apr. 2011.

[37] S. A. Lawal, I. A. Choudhury, and Y. Nukman, “A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant,” *J. Clean. Prod.*, vol. 41, pp. 210–221, Feb. 2013.

[38] E. Kuram, B. Ozcelik, M. Bayramoglu, E. Demirbas, and B. T. Simsek, “Optimization of cutting fluids and cutting parameters during end milling by using D-optimal design of experiments,” *J. Clean. Prod.*, vol. 42, pp. 159–166, Mar. 2013.

[39] N. Andriya, P. Rao, and S. Ghosh, “Dry Machining of Ti-6Al-4V using PVD Coated TiAlN Tools,” in *Proceedings of The World Congress on Engineering*, 2012, vol. III, pp. 1492–1497.

[40] S. Alves and J. De Oliveira, “Vegetable based cutting fluid–an environmental alternative to grinding process,” in *15th CIRP International Conference on Life Cycle Engineering*, 2008.

[41] K. Weinert, I. Inasaki, J. W. Sutherland, and T. Wakabayashi, “Dry Machining and Minimum Quantity Lubrication,” *CIRP Ann. - Manuf. Technol.*, vol. 53, no. 2, pp. 511–537, 2004.

[42] K. V. B. S. Kalyan Kumar and S. K. Choudhury, “Investigation of tool wear and cutting force in cryogenic machining using design of experiments,” *J. Mater. Process. Technol.*, vol. 203, no. 1–3, pp. 95–101, Jul. 2008.

[43] S. Y. Hong, Y. Ding, and W. Jeong, “Friction and cutting forces in cryogenic machining of Ti–6Al–4V,” *Int. J. Mach. Tools Manuf.*, vol. 41, no. 15, pp. 2271–2285, Dec. 2001.

[44] M. P. Groover, *“Theory of Metal Machining”. Fundamentals of Modern Manufacturing*, 3rd ed. John Wiley & Sons, Inc., 2007, pp. 491–504.

[45] S. Kalpakjian and S. R. Schmid, *Manufacturing Engineering and Technology*. Pearson Education, 2006.

[46] D. Dornfeld, *Green Manufacturing*, First. Springer New York Heidelberg, 2013, pp. 68–78.

[47] D. Krajnc and P. Glavič, “A model for integrated assessment of sustainable development,” *Resour. Conserv. Recycl.*, vol. 43, no. 2, pp. 189–208, Jan. 2005.

[48] D. Krajnc and P. Glavič, “How to compare companies on relevant dimensions of sustainability,” *Ecol. Econ.*, vol. 55, no. 4, pp. 551–563, Dec. 2005.

[49] M. F. Ashby, *Materials Selection in Mechanical Design Third Edition*. Elsevier, 2005.

[50] M. F. Ashby and D. Cebon, *Case Studies in Material Selection*. Elsevier Sci & Tech Book Div, 2002.

[51] Dubai Electricity And Water Authority (DEWA), “Tender For The Acquisition Of Cdm Project Opportunities In Dubai , UAE October 2009,” 2009.

[52] “Clean Development Mechanism, UAE Solar Programme of Activities Version.02,” 2012.

[53] D. Kong, S. Choi, Y. Yasui, S. Pavanaskar, D. Dornfeld, and P. Wright, “Software-based tool path evaluation for environmental sustainability,” *J. Manuf. Syst.*, vol. 30, no. 4, pp. 241–247, Oct. 2011.

[54] G. Shao, D. Kibira, and K. Lyons, “A virtual machining model for sustainability analysis,” in *Proceedings of ASME 2010 International Design Engineering Technical Conference & Computers and Information in Engineering Conference ASME CIE .*, 2010, pp. 1–9.

[55] K. Branker, J. Jeswiet, and I. Y. Kim, “Greenhouse gases emitted in manufacturing a product—A new economic model,” *CIRP Ann. - Manuf. Technol.*, vol. 60, no. 1, pp. 53–56, Jan. 2011.

[56] Arcam AB Inc., “Ti-6Al-4V.” [Online]. Available: http://www.arcam.com/wp-content/uploads/Arcam-Ti6Al4V-Titanium-Alloy.pdf. [Accessed: 28-Mar-2012].

[57] C. Richt, “Turning Titanium—Developments in Application Technology,” *Sanvik Coromant, Sandviken, Sweden*, 2003. [Online]. Available: www2.coromant.sandvik.com/coromant/pdf/.../tekn_art_titan.pdf] .Accessed : 17-Nov-2013.[

[58] M. Donachie, *Titanium: a technical guide*. Meterials Park, OH: ASM International, 1988, pp. 75–85.

[59] E. P. DeGarmo, J. T. Black, and R. A. Kohser, *Materials & Processes in Manufacturing*, 10th Ed. Wiley, 2010, p. 529.

[60] ACCU-Svenska AB, “Material Safety Data Sheet (according to EU Directive 91/155/EEC) ECOLUBRIC E200L.” [Online]. Available: http://www.accu-svenska.se/wp-content/uploads/2012/04/ECULUBRIC-E200L-CAS-8002-13-9-eng.pdf. [Accessed: 25-Jan-2012].

[61] B. Boswell and T. T. Chandratilleke, “Air-Cooling Used For Metal Cutting,” *Am. J. Appl. Sci.*, vol. 6, no. 2, pp. 251–262, 2009.

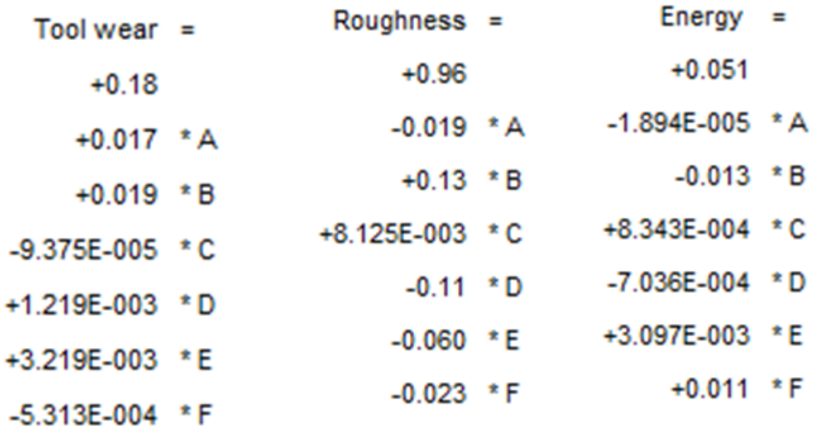
[62] ISO, *International Standard ISO 3685:1993,* Second., vol. 1993. 1993, p. 11.

[63] Y. Su, N. He, L. Li, a. Iqbal, M. H. Xiao, S. Xu, and B. G. Qiu, “Refrigerated cooling air cutting of difficult-to-cut materials,” *Int. J. Mach. Tools Manuf.*, vol. 47, no. 6, pp. 927–933, May 2007.

8. Appendices

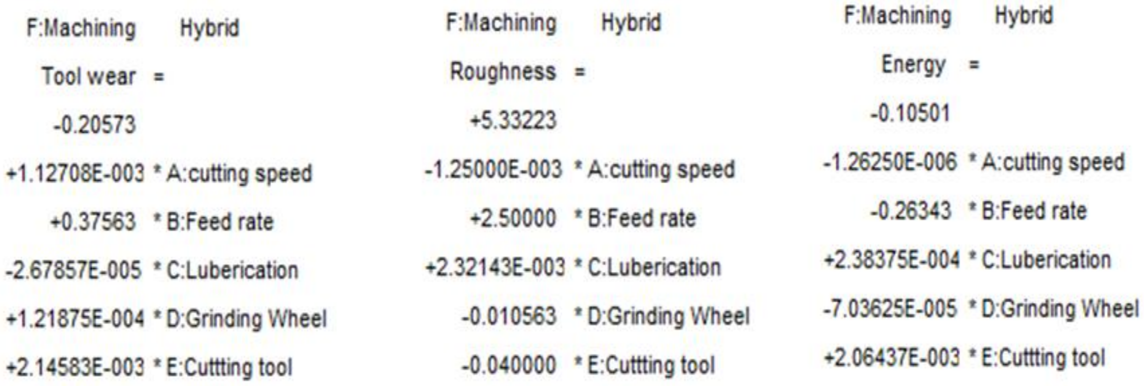
Appendix-A

ANOVA regression model for coded factors (1,-1 as high or low-level of parameters) using Design Expert.



```
Tool wear  =         Roughness  =          Energy  =
      +0.18                +0.96              +0.051
     +0.017  * A         -0.019  * A     -1.894E-005  * A
     +0.019  * B          +0.13  * B          -0.013  * B
 -9.375E-005 * C    +8.125E-003  * C     +8.343E-004  * C
 +1.219E-003 * D          -0.11  * D     -7.036E-004  * D
 +3.219E-003 * E         -0.060  * E     +3.097E-003  * E
 -5.313E-004 * F         -0.023  * F          +0.011  * F
```

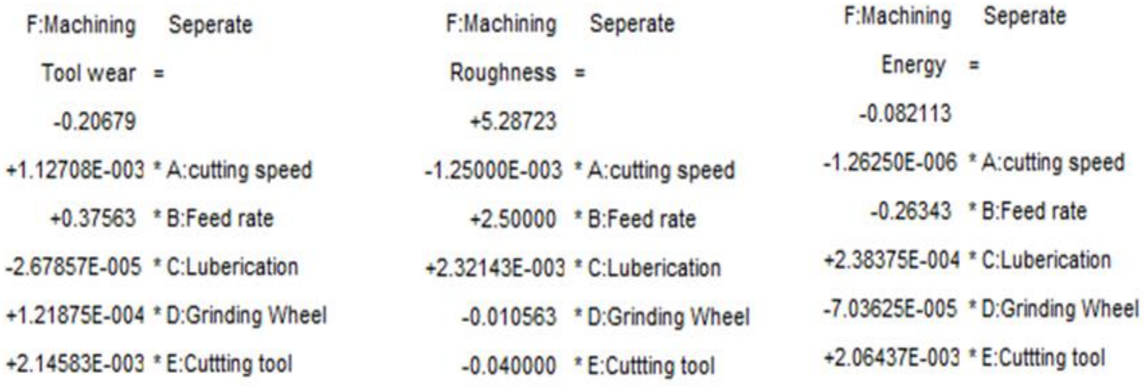
ANOVA regression model for un-coded factors (actual values of parameters)



```
F:Machining    Hybrid
  Tool wear  =
   -0.20573
+1.12708E-003 * A:cutting speed
    +0.37563  * B:Feed rate
-2.67857E-005 * C:Lubercication
+1.21875E-004 * D:Grinding Wheel
+2.14583E-003 * E:Cuttting tool
```

```
F:Machining    Hybrid
  Roughness  =
   +5.33223
-1.25000E-003 * A:cutting speed
    +2.50000  * B:Feed rate
+2.32143E-003 * C:Lubercication
   -0.010563  * D:Grinding Wheel
   -0.040000  * E:Cuttting tool
```

```
F:Machining    Hybrid
     Energy  =
   -0.10501
-1.26250E-006 * A:cutting speed
    -0.26343  * B:Feed rate
+2.38375E-004 * C:Lubercication
-7.03625E-005 * D:Grinding Wheel
+2.06437E-003 * E:Cuttting tool
```



```
F:Machining    Seperate
  Tool wear  =
   -0.20679
+1.12708E-003 * A:cutting speed
    +0.37563  * B:Feed rate
-2.67857E-005 * C:Lubercication
+1.21875E-004 * D:Grinding Wheel
+2.14583E-003 * E:Cuttting tool
```

```
F:Machining    Seperate
  Roughness  =
   +5.28723
-1.25000E-003 * A:cutting speed
    +2.50000  * B:Feed rate
+2.32143E-003 * C:Lubercication
   -0.010563  * D:Grinding Wheel
   -0.040000  * E:Cuttting tool
```

```
F:Machining    Seperate
     Energy  =
  -0.082113
-1.26250E-006 * A:cutting speed
    -0.26343  * B:Feed rate
+2.38375E-004 * C:Lubercication
-7.03625E-005 * D:Grinding Wheel
+2.06437E-003 * E:Cuttting tool
```

Appendix-B

Run	Block #	Feed Rate (mm/rev)	Cutting Speed (m/s)	Lubrication Technique	Tool Wear Vb (mm)	Surface Roughness Ra (μm)	Energy Consumption
1	Block 1	0.2	120	Dry	0.661	1.43	0.019147
2	Block 1	0.1	90	Veg. Oil MQL	0.105	0.91	0.018489
3	Block 1	0.2	90	Cryogenic	0.109	2.27	0.017649
4	Block 1	0.1	120	MQCL Veg. Oil	0.159	0.88	0.030362
5	Block 1	0.1	120	Cryogenic	0.13	1.01	0.018503
6	Block 1	0.1	120	Dry	0.162	0.87	0.031147
7	Block 1	0.2	120	Cryogenic	0.264	1.76	0.012007
8	Block 1	0.2	120	MQCL Veg. Oil	0.591	1.63	0.020033
9	Block 1	0.1	120	Veg. Oil MQL	0.166	0.82	0.012871
10	Block 1	0.1	90	Dry	0.134	1.07	0.028964
11	Block 1	0.2	90	MQCL Veg. Oil	0.18	1.95	0.017722
12	Block 1	0.2	90	Cooled Air	0.212	1.81	0.019154
13	Block 1	0.2	120	Cooled Air	0.676	1.25	0.019647
14	Block 1	0.2	90	Veg. Oil MQL	0.148	2.52	0.011436
15	Block 1	0.1	90	MQCL Veg. Oil	0.11	0.83	0.029753
16	Block 1	0.1	120	Cooled Air	0.336	0.84	0.032041
17	Block 1	0.1	90	Cryogenic	0.077	0.9	0.028773
18	Block 1	0.2	90	Dry	0.166	2.07	0.017922
19	Block 1	0.2	90	Flood	0.12	2.42	0.018701
20	Block 1	0.1	90	Flood	0.099	0.76	0.028904
21	Block 1	0.2	120	Flood	0.206	2.09	0.017854
22	Block 1	0.2	120	Veg. Oil MQL	0.533	1.46	0.008459
23	Block 1	0.1	90	Cooled Air	0.111	0.86	0.030949
24	Block 1	0.1	120	Flood	0.114	0.73	0.030345
25	Block 2	0.1	90	Cryogenic	0.093	0.96	0.028909
26	Block 2	0.1	120	MQCL Veg. Oil	0.402	0.87	0.029919
27	Block 2	0.1	90	Cooled Air	0.116	0.81	0.031193
28	Block 2	0.1	120	Cryogenic	0.122	1.07	0.017003
29	Block 2	0.2	120	Cooled Air	0.664	1.33	0.020112
30	Block 2	0.2	120	Cryogenic	0.171	2.19	0.011374
31	Block 2	0.1	120	Cooled Air	0.15	0.98	0.031177
32	Block 2	0.1	120	Flood	0.132	0.72	0.031369
33	Block 2	0.2	120	Flood	0.321	2.08	0.018531
34	Block 2	0.1	90	Flood	0.112	0.93	0.028677

35	Block 2	0.1	90	Veg. Oil MQL	0.091	0.9	0.017982
36	Block 2	0.1	90	Dry	0.143	0.75	0.028803
37	Block 2	0.2	90	Cryogenic	0.113	2.55	0.017242
38	Block 2	0.1	120	Dry	0.177	0.91	0.031224
39	Block 2	0.2	120	Veg. Oil MQL	0.554	1.38	0.008298
40	Block 2	0.1	90	MQCL Veg. Oil	0.082	0.83	0.030247
41	Block 2	0.1	120	Veg. Oil MQL	0.178	1.33	0.011972
42	Block 2	0.2	90	Flood	0.138	2.09	0.01648
43	Block 2	0.2	90	Cooled Air	0.147	2.16	0.017098
44	Block 2	0.2	120	Dry	0.622	1.49	0.019102
45	Block 2	0.2	90	Dry	0.162	2.55	0.017097
46	Block 2	0.2	90	Veg. Oil MQL	0.169	2.18	0.010652
47	Block 2	0.2	120	MQCL Veg. Oil	0.598	1.92	0.020163
48	Block 2	0.2	90	MQCL Veg. Oil	0.114	2.45	0.016933
49	Block 3	0.2	120	Cryogenic	0.247	1.79	0.011076
50	Block 3	0.1	120	Dry	0.15	0.93	0.030261
51	Block 3	0.2	90	Cooled Air	0.308	1.86	0.018438
52	Block 3	0.1	90	Dry	0.102	0.86	0.028709
53	Block 3	0.2	120	Veg. Oil MQL	0.489	1.62	0.007727
54	Block 3	0.2	120	Flood	0.224	2.2	0.018424
55	Block 3	0.1	90	MQCL Veg. Oil	0.074	0.88	0.029678
56	Block 3	0.2	90	MQCL Veg. Oil	0.163	2.22	0.017888
57	Block 3	0.2	90	Dry	0.141	2.37	0.017478
58	Block 3	0.1	90	Flood	0.101	0.81	0.028382
59	Block 3	0.1	120	Flood	0.111	0.81	0.029983
60	Block 3	0.1	90	Veg. Oil MQL	0.107	0.92	0.017991
61	Block 3	0.1	90	Cooled Air	0.13	0.8	0.029668
62	Block 3	0.2	90	Cryogenic	0.107	0.87	0.017262
63	Block 3	0.2	120	MQCL Veg. Oil	0.607	1.36	0.020141
64	Block 3	0.2	120	Dry	0.534	1.62	0.018998
65	Block 3	0.1	90	Cryogenic	0.096	2.38	0.028592
66	Block 3	0.1	120	Veg. Oil MQL	0.18	0.78	0.012249
67	Block 3	0.2	90	Veg. Oil MQL	0.17	2.06	0.010342
68	Block 3	0.2	90	Flood	0.098	2.35	0.017011
69	Block 3	0.1	120	Cooled Air	0.483	0.93	0.031264
70	Block 3	0.1	120	Cryogenic	0.11	0.85	0.01805
71	Block 3	0.2	120	Cooled Air	0.659	1.31	0.019951
72	Block 3	0.1	120	MQCL Veg. Oil	0.287	1.01	0.031196

Vita

Syed Waqar Raza was born in Sahiwal, Pakistan, on 29th of November, 1987. After getting his early education from O.P.F. Public School Pakpattan, he enrolled in and graduated from Pakistan Air Force (P.A.F) Public School Sargodha with the Academic Roll of Honor. He earned two consecutive Quaid-e-Azam Merit scholarships, the most prestigious scholarship awarded by the educational boards of Pakistan, during 2004 to 2010.

In 2006, after he was selected in the P.A.F, Mr. Raza chose a career in engineering over fighter flying. He got admission in the Industrial & Manufacturing Engineering program at the University of Engineering & Technology (UET) Lahore. He received the second best technical presentation award in the Asia-Pacific Region by the American Society of Mechanical Engineers (ASME) in 2010 and graduated with the University Gold Medal for academic excellence.

After spending a year working in the industry, Mr. Raza moved to the U.A.E. in 2011 and enrolled in the MSME program at the American University of Sharjah. There he also worked as a Graduate Teaching Assistant at AUS from 2011 to 2013.

Mr. Raza likes debates, English prose, Urdu poetry and maintains a keen interest in field Hockey, Cricket and European football.