ASSESSMENT OF ENVIRONMENTAL PERFORMANCE OF MILLING MACHINING

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Thesis submitted in partial fulfillment of the requirements for the Degree Master of Science in Mechanical Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgment any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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ABSTRACT

The manufacturing industry largely contributes to the economy of a country. Thus, manufacturing by material removal processes leaves a significant environmental footprint. This is caused by the influence of process energy, resources, and releases. Due to that, increased attention on sustainable means of machining operations can be seen today. Thus, environmental sustainability assessments and preventive measures are being researched for promoting green manufacturing. In conventional machining, milling is a widely used machining method in the production and manufacturing industries. Thus, the purpose of this study is to assess the environmental performance of milling machining in an industrial setup.

A literature review is conducted to understand the requirement of empirical assessment on sustainable milling and to identify the factors contributing to environmental damage while identifying sustainable machining practices. To conduct the empirical assessments, an industrial milling operation is monitored. At the experiment stage, different consumables and releases are identified and monitored such as power consumption, workpiece material usage, tool material, and coolant while controlling the machining parameters and the tool path. Design of Experiments were used to efficiently manage the controllable machining parameters relevant to environmental performance. The contribution to the environmental damage is analysed and quantified according to the ReCiPe endpoint impact assessment method using SimaPro® (Version 8) life cycle assessment (LCA) software following the guidelines of ISO 14044.

The review revealed several factors that are significantly contributing to the environmental impact. Further, a number of operational level improvements were identified to improve the environmental performance. The results identified the electrical energy consumption and workpiece material usage as the most influencing contributing factors to the adverse environmental impact. Further, an operator’s guide was also developed to harness the operational level savings to ensure the better environmental performance of milling.

Keywords: Sustainable machining; Environmental performance; Milling machining

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LIST OF PUBLICATIONS

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LIST OF ABBREVIATIONS

Abbreviation	Description
LCA	Life Cycle Analysis
Rc	Rough Cut by End Milling
Fi	Finishing by End Milling
Dg	Drilling
Ho	End Milling of a Hole
Re	Reaming
MQL	Minimum Quantity Lubrication
MQCL	Minimum Quantity Cooled Lubrication
Al_2O_3	Aluminium Oxide
Expt.	Experiment
wt%	Percentage by Weight

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1. INTRODUCTION

The industrial contribution of manufacturing plays a vital role in a country's development where machining is performing a prominent subscription in the manufacturing sector. Thus, the sustainability of manufacturing is highly concerned due to the world's changing environmental circumstances. Moreover, sustainable machining is an environmentally friendly, cleaner, and safer method that can reduce waste and power consumption while enhancing operational safety [1]. Further, the improvements in mechanized growth can sometimes lead to less productivity and could adversely influence the overall product life cycle [2]. Traditionally, machining processes are recommended to reduce the cost of production while meeting the industrial production targets, [3] which can lead to environmental damage. Since sustainability closely deals with environmental impact, a wide focus on assessing the environmental impact of machining is becoming a pivotal study area. The environmental impact of machining highly depends on the machine tool operation, [4] where operational strategies can significantly change the environmental impact [5]. However, there has been a lack of studies on sustainable machining practices at the shop flow to concern the environmental impact engaged in CNC milling machining.

Due to the huge involvement in the manufacturing industry, milling machining withstand a substantial environmental impact. Consequently, this research study is based on quantification of environmental impact and sustainable machining practices focusing on the environmental sustainability of milling machining. Life Cycle Analysis (LCA) is used to assess the environmental impact of the study where it is a systematic tool used for assessing the environmental impacts of a product or service [6]. LCA study has been conducted by following its phases: Goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation. In the end, the literature findings along with experimental exposure are used to develop an operator's guideline for the improved environmental performance of industrial milling machining.

1.1 Research aim and objectives

The aim of the research is to promote sustainable manufacturing practices focussing on assessing the environmental performance of milling.

Objectives of this research are to;

1. Identify the key contributing factors to the environmental impact of the milling machining.

2. Assess the environmental impact of a selected industrial milling operation.

3. Develop an operator guideline for improved environmental performance for industrial milling operations.

1.2 Thesis structure

The first chapter covers a brief introduction with a supportive background study. The research aim and objectives are stated in the same chapter with a brief discussion. The second chapter of this manuscript illustrates the literature evidence of sustainable machining and practices refining the research gap. In the second chapter, the key contributing factors and shop flow practices that affected milling machining have been identified and discussed.

The methodology followed to carry out this research is presented in the third chapter. The third chapter briefly explains the research design, planning of experiments and guideline preparation method. Experimentation and data analysis are allocated to the fourth chapter. In the fourth chapter, quantitative identification of energy, other consumables and releases have been conducted. The fifth chapter presents the results and discussion of the study. The conclusion is included in the sixth chapter. The appendices are attached at last.

1.3 Study preface

The problem for this study has been identified through a literature review focused on milling machining. The literature findings were well matched with the research objectives to be considered in the study. The key contributing factors to the environmental impact of milling machining were targeted in the literature content while identifying a research gap to be addressed focusing on the environmental impact of milling machining. The knowledge contribution has enclosed the unfilled research area through the research outcomes.

This study concerns the environmental impact of milling machining. It focuses on the environmental impact assessment of milling machining and the preparation of an operator's guide with an emphasis on sustainable means of milling machining. As the initiation, a literature survey has been conducted. The key contributing factors and shop floor practices that influence the environmental impact are identified. The experiments were conducted on a CNC milling machine considering an industrial case study. An energy data logger has been used for the data collection process where the logger can provide accurate measurements of energy-related parameters. Thus, a consumables and releases study has been conducted to gather information on other impact factors that affect the environmental impact. LCA has been performed using SimaPro software to quantify the environmental impact due to ascertained energy, consumables, and releases. As an outcome, a sustainable milling machining guideline has been developed for operators, using the literature outcomes along with experiment outcomes.

2. LITERATURE REVIEW

2.1 Background

Milling is an important conventional machining process that feeds work against a rotating cutter. The energy used to power the machines is usually electrical. Thus, electrical energy consumption for the material removal process is directly accountable for the environmental impact [7]. The electrical energy consumption of machines is responsible for more than 90% of the environmental impact of conventional machining [8]. The generation of energy consists of emissions due to its energy production method(s). Jeswiet and Kara [9] projected a mathematical model to assess Carbon Emission (CE) by using Electrical Energy Consumption (EC) and Carbon Emission Signature (CES) as follows,

$$CE = EC(GJ) \times CES(kgCO_2/GJ) \qquad (01)$$

Since carbon emissions straightly cause global warming, most countries try to decrease their carbon emissions by introducing and using sustainable energy generation methods using solar energy, wind energy, sea wave energy, etc. For example, US Energy Information Administration contributed towards environmental sustainability by reducing its energy-related carbon dioxide emissions by 89 million metric tons, from 2015 to 2016 [10]. Thus, individual companies also try to increase the company's reputation by being carbon neutral to decrease environmental damage.

Carbon footprint is a popular method to represent the environmental impact. The environmental impact can represent with different methods such as the person equivalent (PE) method where one PE is the annual impact caused by an average person and is calculated for each category by dividing society's total annual impact by the number of inhabitants [11].

International Energy Agency confirms that energy-related CO_2 emissions are continuously increasing from since 1970. However, there was no significant growth in emissions in 2015 and 2016 compared to that of 2014 as shown in figure 2.1.

Thus, this study reviews and assess the environmental implications caused by the operational parameters, techniques, and conditions of milling.

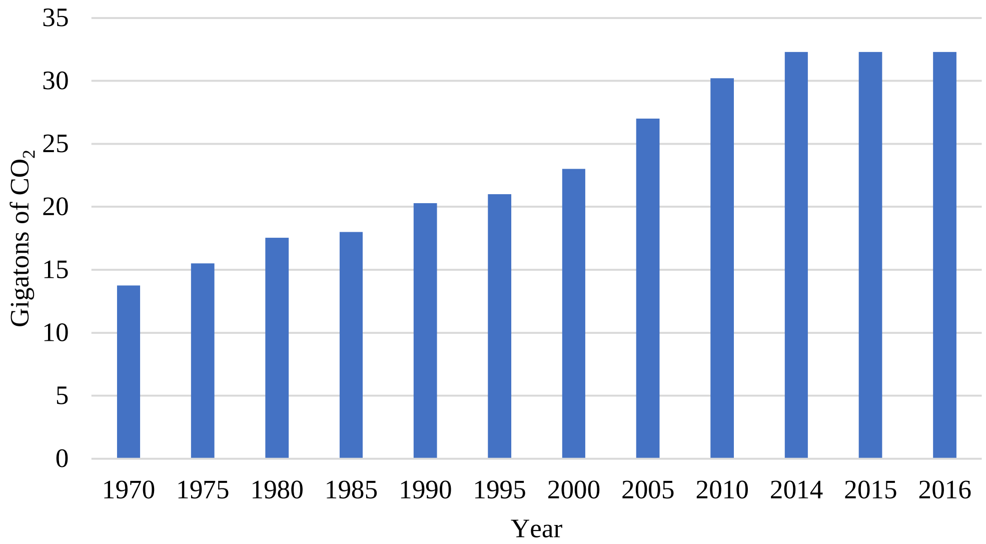

Figure 2.1: Global energy-related CO_2 (Gigatons) emissions [5]

The review starts briefly discussing the impacts of world energy consumption in general and then narrows down to manufacturing process energy. Then it focuses on modern machining techniques followed by a detailed analysis of the environmental performances of milling machining focusing on the contribution factors and operational techniques. Other causes that affect the environmental impact are also briefly discussed.

2.2 Factors affecting the environmental impact

The environmental impact of the machining process highly depends on the primary and secondary factors specific to a particular machining setup. Several major factors that vary the environmental impact have been identified through the literature review such as energy consumption, material usage, cooling, tool path design, tool design, product design, and machining parameters. Energy consumption has been recognized as the most identical controllable factor that can affect the environmental impact. Thus, energy consumption is indirectly controlled by other primary factors. Then the process of energy consumption is linked to the primary factors and discussed more descriptively.

2.3 Environmental impact of manufacturing

The total energy consumption in the world has been increasing, probably triggered by the industrial revolution, and continues to increase to cater to the rising population and their ever-increasing needs. The greenhouse gas emissions are also continuously increased since the seventieth century [12]. The global average temperature level is increased by the increase of greenhouse gases in the atmosphere. The use of renewable energy sources is tending to decrease energy-related emissions. However, various categories of barriers can be identified when proceeding with renewable energy initiatives. Major barriers include economic and financial barriers, market barriers, technical barriers, and institutional barriers. Solutions for these barriers might unique to a country/region [13].

Reduction of energy consumption seems a better way to reduce the environmental impact and on the other hand, increasing the composition of renewable energy sources will also act in favour of the environment. A case study done in Turkey forecasts that renewables will be even more cost-competitive and affordable compared to fossil fuels by 2040 considering the forecasted popularity of renewable energy sources for the next 30 years [14]. At the same time, the usage of non-renewable energy sources could also be increased in many countries following the typical trend. For example, China's share of nuclear generation is forecasted to increase from 3% in 2015 to 11% in 2040. Over the same period, its natural gas share will be increased from 2% to 7%. Japan is a country with a substantial nuclear contribution, committed to the challenge of reducing its greenhouse gas emissions by 25% by 2030 [15]. Energy consumption of the manufacturing sector amounts to a significant portion of the world's energy consumption and is responsible for significant environmental impact [16]. The energy usage of a specific manufacturing process can either be measured or estimated. Different methods and equipment are used to measure energy consumption, such as portable energy logging /metering/ equipments or dedicated apparatuses. Models or frameworks can be used to estimate the energy consumption in a product manufacturing system. Different manufacturing processes need to be followed by different frameworks to calculate energy consumption [17]. For example, the fundamental energy demand model is proposed to calculate the total energy consumption as shown in Equation 02.

$$E = (P_0 + k\dot{v})t \qquad (02)$$

Where E represents the total energy for the manufacturing process in J, P_0 is the power in W demanded by the production device (in this case, the machine tool is operating at zero loads), t is the production time in s, $\dot{v}$ is the rate of material processing in mm^3s^{-1} and k is specific cutting energy consumption in $Wsmm^{-3}$ [18]. More energy consumption models are presented in Table 2.1 of Section 2.5 directing the milling operations. The specific energy consumption (SEC) can be used to represent the energy consumption of a unit process [19].

2.4 Environmental impact of modern metal cutting techniques

The use of Computer Numerical Control (CNC) machines became more competitive since the late nineties. The energy consumption of CNC machines is comparatively greater than the energy consumption of manual machining methods due to their large number of subunits. In general, manual machines consume less energy compared to CNC machines to eliminate a given volume of material at a specified spindle speed. Further, it has been found that more than 50% of energy is consumed for non-cutting operations of CNC machining [20]. It is further evidence that the machining time is less than the total machine operating time. Research conducted using a series of experiments on ten (10) CNC machines has found that the mean power employed throughout the working cycle is equal to or less than 50% of the total power and the productive time is only about 60% [21]. The energy measurements should be accounted for all relevant input and output flows such as electrical energy, coolant, compressed air, and any other utilities. [22]. In general, the major component of the machining cost is formed by the cost of energy. Moreover, it yields the highest negative impact on the environment [3].

A study using two CNC milling machines, four CNC lathes, and a machining centre shows that the energy consumption of non-cutting motions is dependent on the machine tool whilst the energy consumption of turning is almost independent of the machine tools [23]. The overall power consumption (P_{total}) in turning has been modelled as the sum of productive power consumption and machine power consumption ($P_{machine}$) in J. Where, productive power is taken as the multiplication of material removal rate (Q) in cm^3s^{-1} and specific energy consumption (k) in Jcm^{-3} [24], [25].

$$P_{total} = P_{machine} + k \times Q \qquad (03)$$

Another experimental model for turning operation shows that the power consumption can be reduced with the maximum possible values of feed rate and depth of cut [26]. However, higher feed rates would lead to poor surface outcomes [27]. When the cutting/spindle speed is considered, high-speed cutting consumes lower energy than that with standard cutting speeds [28]. Lower specific energy consumption can be achieved by the higher depth of cut, feed rate, and spindle speed in turning. The machining process encountered a loss due to an additional load. It is found that the additional load losses depend on cutting power and it is a second-order function of the cutting power of the turning process [29]. Grinding is a wide practice machining technique when focusing on conventional machining. In grinding, energy varies with the change of workpiece speed, infeed rate, and speed of the grinding wheel. Thus, grinding energy can be significantly decreased by lubricants [30].

When considering unconventional machining energy, the major portion of environmental damage is produced by process energy which is of similar scales to conventional machining. It is found that the approximated environmental impact of 60% is caused by process energy with four cases of Wire EDM and Die-sinking electro-discharge machining (EDM), with two workpiece materials [31].

Process energy is affected by a considerable portion due to standby energy. A study using nine machining centres has shown that there is a significant variation of standby energy based on the machine type and the complexity of the machining centres with high automation [32]. Both optimisation of processes and machine design to decrease the standby time can decrease the energy consumption of milling and turning [33]. These variations are further evidenced by a case study of press-brake units, where the standby energy consumption has shown significantly different values, 83%, 43%, and 27% of total energy, for three industrial press brakes [34].

Most of the machining processes work with metals as the workpiece material where the cutting tool always represents a metal as the making material. Then the impact of the metal production process is to be considered especially in this study. Thus, metal production leaves a significant impact on energy consumption and the environment [35]. A research work found that greenhouse gas emissions and global warming are critical environmental factors that refer to the environmental impact of metal production [36] where metal production initiates the environmental damage starting from mining [37], [38].

2.5 Environmental impact of milling machining

Milling is an important machining method in metal cutting. Milling energy depends on the nature of the work and machine tool specifications. The non-cutting activities such as tool/work retraction and positioning and triggering of sub-units are governed by the numerical coding/program of the machine tool. Significant optimization of the non-cutting activities, such as increased material removal rate and replacement of sub-units with low-energy alternatives can decrease the energy requirement of milling machining [39]. Further, less total specific energy can be achieved by higher material removal rate with less cutting tool embodied energy[40], [41]. The energy utilisation in machining depends largely on the design (material selection, part geometry) and set-up (cutting-fluid selection) parameters, whilst waste-stream production and processing time are influenced by design (workpiece material and part geometry) and operating (speed and feed) parameters [42]. The tool path designs with shorter cycle times can yield greater environmental and manufacturing performance synergies by dropping energy consumption [8].

Milling energy consumption varies with the machine type [43] and the size of the machine [44]. Most manufacturing energy models are developed by using empirical or analytical methods. In some cases, hundreds of machines are experimentally and statically analysed to launch a mathematical model to forecast the electrical energy consumption [45]. The product-based energy consumption model depends on three factors: the process parameters, the product design, and the specific circumstances within the manufacturing system [17]. A study followed a hybrid approach to the slot milling energy model where an analytical cutting force model is used to obtain the cutting energy at the tooltip and the total energy is captured experimentally characterising method. Machining energy prediction is conducted by applying this hybrid method [46]. Table 2.1 shows a summary of milling energy models.

Table 2.1. Energy models used in milling

Model	Nomenclature	Eq. No.	Ref.
$\boldsymbol{E_c = P_1(T_1 + T_2) + P_2(T_2) + P_3(T_3)}$	P_1 − Constant power during machining operation regardless of running state (basic power) P_2 – Power for cutting by spindle and servo motor P_3 – Power consumption to position the work to accelerate/decelerate the spindle to the specified speed T_1 − Cycle time during the non-cutting stage T_2 − Cycle time during the cutting stage T_3 − Time required for the position the work and to accelerate the spindle	(04)	[47]
$\boldsymbol{E_C = (P_0 + kQ)t}$	P_0 − Power consumed by machine module k – Specific cutting energy requirement for the particular workpiece material Q − Material removal rate t − Cutting time	(05)	[25]
$\boldsymbol{E_C = (P_{cut} + P_{air}).\Delta T}$	P_{cut} - Power demand for cutting P_{air}- Power demand for air cut ΔT- Processing time	(06)	[48]
$\boldsymbol{E_C = E_{spindle} + E_{feed} + E_{tool} + E_{coolant} + E_{fix}}$	$E_{spindle}$ − Energy consumption of spindle including the spindle transmission module and energy requirement for material removal from the workpiece E_{feed} − Energy consumption of axis feed E_{tool} − Energy consumption of tool change $E_{coolant}$ − Energy consumption of tool change E_{fix} − Energy consumption of fan motor and servo system	(07)	[49]
$\boldsymbol{E_C = P_0 t_1 + (P_0 + kQ)t_2 + P_0 t_3\left(\frac{t_2}{T}\right) + y_E\left(\frac{t_2}{T}\right)}$	P_0 – Power consumed by machine module without cutting t_1 − Machining setup time t_2 − Actual cutting time t_3 − Tool change time T − Tool life y_E − Energy footprint per tool edge k − Specific cutting energy Q − Material removal rate	(08)	[50]

$$\boldsymbol{E_C = E_{fixed} + E_{axes} + E_{axis\ chillers} + E_{spindle} + E_{spindle\ chiller} + E_{chip\ conveyor} + E_{tool\ change} + E_{pallet\ clamp}}$$	E_{fixed} − Energy required when the machine is switched on E_{axes} − Energy required for axis which composes of rapid movement, approach workpiece at working speed and during machining $E_{axis\ chillers}$ − Energy consumed by axes chillers $E_{spindle}$ − Energy of both the cutting power and the spindle losses $E_{spindle\ chiller}$ − Energy consumed by spindle chillers $E_{chip\ conveyor}$ − Energy consumed when the chip is removed $E_{tool\ change}$ − Energy consumed for tool change $E_{pallet\ clamp}$ − Energy consumed for clamping the pallet	(09)	[51]
$$\boldsymbol{E_C = SEC.Cutting\ Volume}$$ $$\boldsymbol{SEC = C_0 + \frac{C_1}{MRR}}$$	SEC − Specific Energy Consumption C_0 and C_1 − Machine-specific coefficients MRR − Material Removal Rate	(10)	[52]
$$\boldsymbol{E_C = E_{const} + E_{run-time-transient} + E_{run-time-steady} + E_{cut}}$$	E_{const} − Energy consumed not related to machining $E_{run-time-transient}$ − Energy consumed by the spindle, machine axes, and tool change when accelerating or decelerating to reach specified values $E_{run-time-steady}$ − Energy consumed by the spindle, machine axes, and tool changes when the spindle motor and the axis drives keep a specified value E_{cut} − Energy consumed by material removal action	(11)	[53]
$$\boldsymbol{E_t = C_0 + \frac{C_1 D\pi}{1000na_p a_e vf}}$$	C_0 and C_1 − Machine tool dependent variables D − Cutting tool diameter in mm n − Number of teeth a_p − Axial depth of cut in mm a_e − Radial depth of cut in mm v − Cutting speed in m/min f − Feed rate in mm/tooth.	(12)	[54]
$$\boldsymbol{SEC = k_0 + k_1\left(\frac{n}{MRR}\right) + k_2\left(\frac{1}{MRR}\right)}$$	n − Spindle speed k_0, k_1, and k_2 − Coefficients related to the machine tool MRR − Material Removal Rate	(13)	[55]

The cooling method significantly affects the energy consumption of the milling process. A study on end-milling proves that dry machining requires 10% less energy compared to minimum quantity lubrication (MQL) under similar working conditions except for cooling. Dry machining consumes 38% less energy compared to flood cooling. Thus, flood cooling consumes more energy compared to MQLand dry machining due to the energy consumption of sub-units, in this case [56], [57]. The use of MQL and alternative cooling techniques were suggested as eco-friendly replacements instead of flood cooling [58]. The net energy consumption not only depends on individual process parameters but also depends on the nature of the tool and the cutting mode (up or down milling). It is found that 11.3% net energy increase arose for up milling compared to down milling while machining with a sharp tool and 4.7% energy increase for up milling with a worn tool [8].

When considering the cutting fluid, the use of Nanofluids has shown improved performance on energy footprint [59]. The use of Nanofluid lubrication in milling is a new area of research. In a research, Nanofluid is made by mixing Silver Nanoparticles and powder of alumina (Al_2O_3) with water. Then the Nanofluid is used as tiny drops to perform MQL on turning operation. Then machining outcomes are compared with dry machining and decomposable emulsion. The results showed that alumina Nanofluid decreased tool wear, cutting forces, and chip curling while machining [60]. A research study used 35 nm and 80 nm diameter Nanoparticles with vegetable and oil-based Nano coolants and tested with a pin-on-disk friction tester has found that the graphite Nanoparticles improve the anti-wear properties while reducing the friction [61]. Two different types of graphite have been used with 0.1–0.5 wt% solution in an experiment to study the variations of cutting force. The average diameters of platelet types were 1 mm and 15 mm, respectively. Micro milling has been done with hardened steel. Results showed that the cutting force depends on graphite concentration, graphite size, and lubricant flow rate [62].

Disposal of contaminated fluid in machining keeps a significant environmental footprint due to eco-toxicity. Further, coolants are responsible for greenhouse gas emissions. It is recommended to use an eco-friendly cooling technique such as MQL and cooled air lubrication to reduce the cutting fluid disposals and emissions [63]. Recycling cutting fluid is identified as an effective way to reduce the environmental impact where a few researchers proposed a method to recycle the cutting fluid effectively [64].

Metal chip disposal makes a large environmental damage. Recycling metal chips can reduce the environmental impact of disposal [65]. Sorting of metal chips is identified as a barrier to the recycling process and new technologies are now available to sort the chips [66]. Thus, it is important to use eco-friendly technologies for the recycling process [67].

Tool wear greatly affects the tooltip energy consumption. Thus, the reduction of tooltip energy can reduce the electrical energy usage [8]. In some milling operations, the tooltip energy usage is comparatively low whereas the energy usage of auxiliary components is bulky. It is found that the tip energy consumption is only 19% of the total and thus the design of machine tools needs to optimise the energy demand with controls, lights, and spindles to reduce the total energy usage [68].

In general, the milling force coefficients are determined, and tool designs are modified using empirical outcomes. For example, it is found that many empirical results are needed to develop complex cutting tools such as ball-ended helical milling tools. Also, the cutting force is forecasted by a semi-mechanistic cutting force model using empirically identified cutting coefficients on the flank and rake contact surfaces [69]. A study proposes a method to forecast the cutting forces and milling force coefficients in end-milling which can be extended to any cutter geometry without milling cutter calibration tests. The comparison of the proposed method with a mechanistically calibrated method has shown equal results [70].

The properties of the workpiece materials influence the energy footprint of milling. For example, milling titanium alloys use higher energy compared to steel or aluminium [20]. Further, it depends on the properties of the cutter where energy usage is not obvious. Manufacturing process of a milling tool consumes a bulk of energy. Thus, the energy for tool manufacturing mainly consists of energy embodied in sintering (and grinding for some tools), material selection, and coating processes on multiple tooltips [50]. For a manual cut, operators should have a good sight of the cutting edge when machining happens inside a smoke of coolant through the viewing window [71].

Deterministic or non-deterministic assessment methods are used for the sustainability assessment of a manufacturing system [72]. Life cycle assessment (LCA) and Environmental effect analysis (EEA) are widely used Desing of Environment (DfE) methods that assess/predict the environmental impacts. Though LCA is an effective method for environmental assessment, industrial applications are limited due to the high investment of time and the need of large data requirements. A study showed that only 18% of users used the LCA method for their research among 175 respondents [73]. Analysing the environmental and economic performance under the framework of LCA and Life cycle cost (LCC) analysis can be used to choose the best alternative out of different designs [74].

Research on LCA claims that the quality of machined parts make an indirect environmental burden where it can be identified as a secondary effect on the environment[75]. Low volume and high variety manufacturing processes need effective scheduling and process planning of the machine shops. Operations sequence and the machining features need to consider while scheduling the machining processes. The basic three types of shop floor arrangements can be identified as a process, product, and hybrid layout [76]. Generally, the product variety and the number of production quantities use to select the shop floor layout where process layout is preferred with high varieties and product layout suited for mass production. Hybrid layouts, also known as cellular layouts, consist of the characteristics of both process and product layouts. Further research is needed on the shop floor energy consumption considering the ventilation, heating, air conditioning, and compressed air requirements [77].

2.6 Conclusion of the literature and research gap

The milling energy usage and the resulting environmental footprint are investigated in this review. The outcomes show that milling energy leaves a considerable environmental impact and the non-machining energy component is significant. Further, the review reveals the parameters can be controlled to reduce process energy consumption. More comprehensive cooling techniques such as MQL, cryogenic cooling, Nanofluid lubrication, solid lubrication, and cold air cooling are proposed instead of flood and dry machining to decrease the energy-related environmental impact caused by cooling. Optimised process parameters may support low energy consumption. Thus, higher material removal rates perform low specific energy consumption where milling energy models are helpful to take a better understanding. Milling energy depends on the cutting tool geometry, where properly designed cutting tools lead to low energy consumption. Further, optimised tool paths cause low energy consumption saving from unnecessary motions. Machine choice is an important aspect based on the job, for example, micro-milling can be performed on a small milling tool with low process energy. The machining quality influences the energy consumption of the use phase of the machined item. Thus, better operations planning and scheduling of machine shops could reduce the process energy consumption. In conclusion, the review has presented the significance of contributing factors of conventional machining operations on the process level environmental impact. Operations-related improvements were also identified which are practiced in the industry or proposed by research.

Overall, the environmental impact of milling machining operation is highly dependent on the key contributing factors where the factors are highly affected by both the milling parameters and machining practices. It reveals a need for sophisticated environmental impact assessment over the milling process by focusing on the contributing factors while varying the key milling parameters. Further, it identified a lack of studies on sustainable milling machining practices in the shop flow.

3. METHODOLOGY

The research is designed as presented in Figure 3.1 which follows a sequence of steps to compile the research outcomes. Initially, a literature review has been conducted. The review findings have refined the research gap. Considering the second step, the design of experiments has been conducted with the help of literature findings and Taguchi arrays.

3.1 Research design

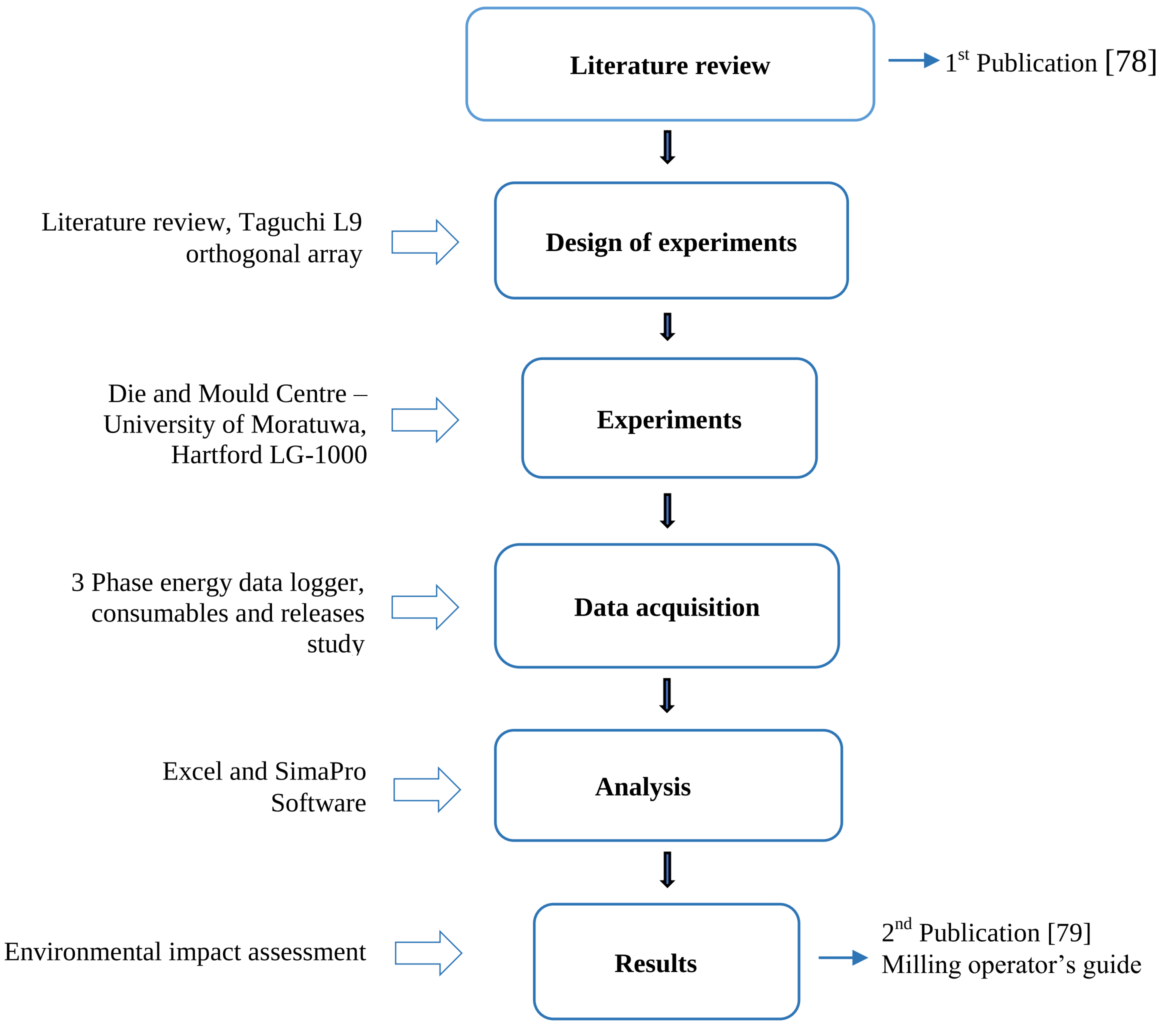

Figure 3.1: Research design

The experiments were designed based on Taguchi L9 orthogonal array as inspired by the review. 'Hartford LG-1000' milling machine was used for the machining trials.

Experiments were conducted to take measurements of energy, other consumables, and releases. A 3-phase energy data logger (Fluke 1736) was used to capture electrical energy consumption. SimaPro® software and MSExcel were used as analyzing tools. SimaPro® is a product system modelling and assessment software released in 1990 which is commonly used in LCA [12]. The software includes a user interface for modelling the product system, the access to Life cycle Inventory (LCI) database, and impact assessment methods [80]. Finally, the environmental impact of the milling operation has quantified while proposing an operator's guide for CNC milling machine operators.

ISO 14040: LCA principles and framework, with ISO 14044: LCA requirements and guidelines are the primary standards that cover the LCA procedures [81]. ISO 14044 highly depends on LCA which can be used to discuss specific issues related to the LCA field such as discussing the critical reviews on environmental impact, sustainability, product comparison, good practices, benchmarks, indeterminacy, and carbon footprint [82].

The LCA software needs to refer to an LCI database, which is Ecoinvent in this case. The Ecoinvent database is a comprehensive database that has provided access to SimaPro software. At the same time, SimaPro offers sophisticated analysis methods such as Eco-indicator 99, CML 2001, EDIP 97, Impact 2002+, and ReCiPe. Ecoinvent database consists of a central database, calculation routines, editor, administration tool, query tool, data (exchange) format, local databases, and a highly connected and matched database such as Ecoinvent is needed to create a database of centralised life cycles [83]. The Ecoinvent project partners' common goal has been to make LCA easier by obtaining LCI data from a consistent generic background [84]. Moreover, Ecoinvent version 3, the latest at the time, was used for this study.

ReCiPe is one of the most recent life cycle assessment methods which focuses on the midpoint and endpoint environmental assessment categories [85]. The endpoint categories are directly related to midpoint categories where the endpoint categories are derived from the midpoint categories with the help of the mid-to-endpoint factor [86]. Thus, the endpoint approach provides a complete picture of the whole assessment results considering three impact categories as human health, ecosystems, and resources [87] where the outcomes are generally more understandable for decision making [88]. Therefore, ReCiPe Endpoint version is used as the LCA method to represent the results as an overall outcome.

After the quantification of environmental impact, the behaviours of operational parameters influenced the experiment outcomes are studied. Thus, the operational techniques used to control the impact are studied at the literature review. The operator's guide is developed by studying and mapping the experimental outcomes and literature outcomes.

3.2 Review method

Every research work needs to have a strong literature review as its foundation to start and clarify the correct research idea. The literature review of the research work should need a methodical way to establish the meaning [89]. Thematic cording method has been used as the literature analytical method in this study. Thematic coding is an important method that refers to the qualitative study of research review where the data can be categorized accordingly [90]. The categorization is conducted by establishing the themes. The basic features affect the environmental impacts were identified as themes.

The themes are established in the initiation of the research work to classify the main review findings. Thus, subthemes are also implemented in the review to achieve a comprehensive identification [91]. As an initiation, the first theme has been identified considering the sustainability which consists of three major subthemes the importance of machining sustainability, sustainable principles, and the importance of environmental performance analysis. ‘Energy consumption and energy optimization methods’ is identified as the most important theme where it has several subthemes such as the environmental impact of manufacturing, the environmental impact of modern metal cutting technologies, and the environmental impact of milling machining. Operational practices to reduce the environmental impact such as cooling, tool path designs, tool designs, machining parameters, and product designs are further referred. The use of Microsoft Excel for thematic coding is allowed the user to make easy access while showing a complete result in one data sheet [92]. Then to compromise the research details, the identified themes and subthemes were systematically arranged with a help of an Excel worksheet.

3.3 Design of experiments

The experiment setup was aligned with an industrial case. A Low-Alloy steel workpiece is milled to get a shape as depicted in Figure 3.2. The features of Figure 3.2.b are considered for continuous machining, without changing the clamping. Different parameter combinations were used to cut the same part with the permission of the machining centre staff. Unit volume of material removal is considered for all parameter setups which can be considered as the functional unit for the study. Machining is performed with five sequential cutting operations: rough cut, finishing, drilling, end-milling of a hole, and reaming.

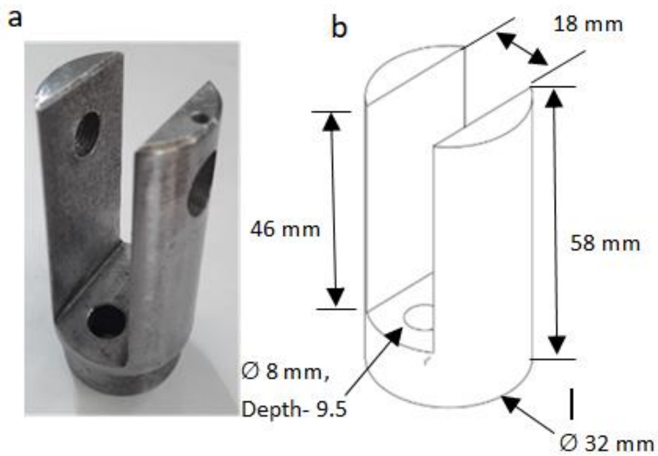

Figure 3.2: (a) Actual part to be machined; (b) Considered part features for the study

3.3.1 Experimentation process

Initially, an industrial milling operation has been chosen to access the environmental effect. Different consumables and releases are monitored considering the milling operation. The existing previous data and the ongoing behaviours of the machining process have been studied to gather exact information about the inputs and outputs of the machining operation. Energy consumption in the machining process has taken place as an iconic focus which needed careful investigation to collect energy data. Where, Fluke 1736 three-phase energy data logger was used to capture electrical energy consumption.

SimaPro® LCA software has been used to analyse the environmental impact associated with the milling processes. Thus, this research is based on the sustainability assessment of milling which is considered under ISO 14044 guidelines. The LCA software has been used to follow those guidelines in using standards. Ecoinvent version 3 is used in this study to have a better database and the ReCiPe Endpoint (H) version is used as the method for the analysis.

3.3.2 Control parameters and parameter levels

The selection of control parameters is an important step of experiment design where the outcomes of the study highly depend on the selected parameters [93]. Three basic machine parameters were used as control parameters for the study namely depth of cut, feed rate, and cutting speed [94], [95].

A high number of parameter levels give accurate combinations of results concerning the experiment combinations. Three levels are assigned to parameters to enrich the combination of experiments. The first parameter level is decided by taking the actual value which is used by the operators. The second level is calculated by referring to the cutting tool catalogue for cutting low-alloy steel. The third level is calculated by apportioning the first and second parameter levels. Table 3.1 presents the parameter levels. The meanings of the symbols are given in the nomenclature.

Table 3.1: Parameter levels

Level	**Depth of cut (mm)**					**Feed rate (mm/min)**					**Cutting speed (rpm)**				
	Rc	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**
1	5.75	2	2	0.13	9	50	340	25	110	15	700	1800	650	3200	250
2	7.5	6	2	0.13	9	90	520	82.5	405	65	732	1592	1386	2122	1512
3	6.625	4	2	0.13	9	130	700	140	700	115	764	1696	1018	2661	881

3.3.3 Taguchi L9 orthogonal array

Taguchi method is a strong design approach that can obtain robustness in the process or product design [96], [97]. Thus, it is a powerful and unique technique to improve the quality of work while optimally setting the controllable factors [98]. Research findings recommended using Taguchi's robust design approach with metal cutting studies [99]. Twenty orthogonal arrays exist [100] and the most suitable array type should have to be selected by considering the number of control parameters and their levels [101]. The experiment design consists of three control parameters with three-parameter levels for each. Further, a research team used the L9 orthogonal array to design their experiment structure successfully, where the same number of control parameters and levels existed for the study [102]. Then the experiment design of the research study is in line with Taguchi's L9 orthogonal array with successive proofs. Taguchi L9 orthogonal array is used to design the experiments by meshing the parameter levels. Experiment numbers indicate the different parameter combinations for the same milling geometry. Table 3.2 shows the experimental setup.

Table 3.2: Experimental setup

Exp No. (*3)	Depth of cut (mm)					Feed rate (mm/min)					Cutting speed (rpm)				
	Rc	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**
1	5.75	2	2	0.13	9	50	700	25	700	15	700	1800	650	3200	250
2	5.75	2	2	0.13	9	130	340	140	110	115	764	1592	1386	2122	1512
3	5.75	2	2	0.13	9	90	520	82.5	405	65	732	1696	1018	2661	881
4	7.5	6	2	0.13	9	50	700	25	700	15	764	1592	1386	2122	1512
5	7.5	6	2	0.13	9	130	340	140	110	115	732	1696	1018	2661	881
6	7.5	6	2	0.13	9	90	520	82.5	405	65	700	1800	650	3200	250
7	6.625	4	2	0.13	9	50	700	25	700	15	732	1696	1018	2661	881
8	6.625	4	2	0.13	9	130	340	140	110	115	700	1800	650	3200	250
9	6.625	4	2	0.13	9	90	520	82.5	405	65	764	1592	1386	2122	1512

3.4 Data acquisition

Data acquisition of a manufacturing process needs accurate methods and procedures to manipulate precise data acquirements. Computer numerical control machining is a major part of manufacturing that needs significant attention of data acquisition and monitoring refers to intelligent manufacturing [103]. Different manufacturing systems need various data acquisition approaches by considering the objectives and the conditions of the system [104]. Data acquisition of this study has different aspects where the data acquisition of energy consumption played an important role. The raw energy data consumption has been recorded by the use of a precise energy data logger which needs a secondary data acquisition method. The logged energy data has been exported to a Microsoft Excel worksheet to convert the raw data to meaningful information.

4. EXPERIMENTATION AND DATA ANALYSIS

4.1 Environmental performance analysis

Life cycle assessment (LCA) methodology has been followed to perform the environmental performance analysis of this study. LCA Products designed with waste minimization activities and associated design and manufacturing will reduce the environmental pollution of the products as well as the price [14]. The guidelines of ISO 14044, 2006 were followed to conduct the experiments of the study. According to ISO references, LCA has to conduct by following four systematic phases such as goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation [105]. Figure 4.1 shows the relationship between the four LCA phases.

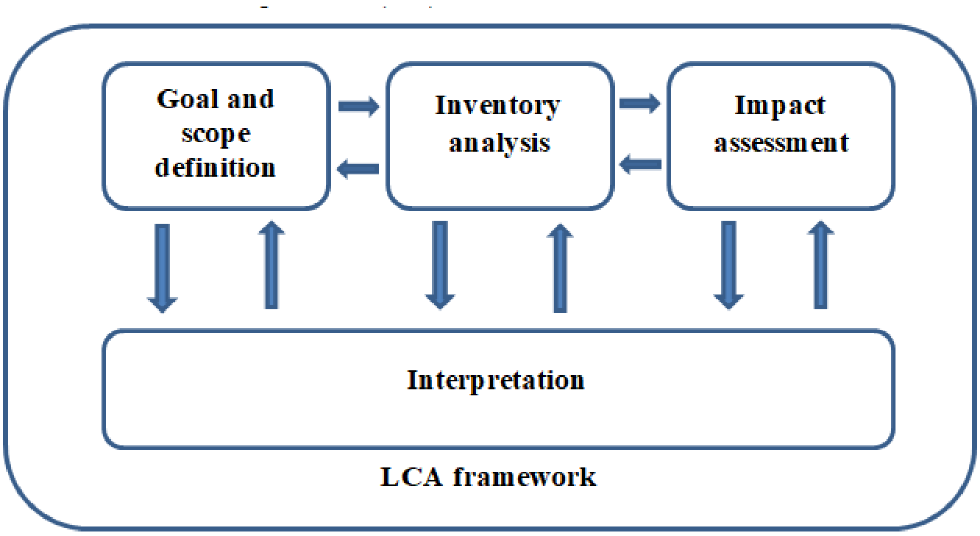

Figure 4.1: Phases of an LCA

4.1.1 Goal and scope

The initiation of an LCA is established with the goal and scope definition, where it provides the details of the system boundary and functional unit [106]. The quantification of the environmental impact of an industrial milling machining process is the goal of the LCA study. The selection of boundaries for an LCA study is highly considerable, where the results of the LCA study depend upon the boundary definition [107]. In the considered LCA process, the boundaries were imposed on the consumables and releases covered by energy consumption, workpiece material, tool material, water, and petroleum oil. The establishment of a functional unit is an important activity where the considered environmental assessment study gets unique with the selection of the correct functional unit [108]. A specific volume of material removal in an industrial-related milling process is identified as the functional unit for the LCA study.

4.1.2 Life cycle inventory analysis

The life cycle inventory analysis was the most time-consuming part of this LCA study, where a series of related measurements and calculations were imposed to take the inventory data. The life cycle inventory factors may affect the environmental impact with indirect environmental load factors and direct environmental load factors [109]. Usually, dedicated software is used in inventory modelling [110]. Thus, SimaPro software is used to model the inventory for this LCA study. It is difficult to gather all the information on inventory factors, where the access to some fine data of the system is working with some constraints [111].

4.1.2.1 Energy study

The energy data logger (Fluke 1736) was used to log the process energy consumption of the machining processes. The data logger can provide accurate measurements of voltage, current, and energy usage. It provides the outputs with more than 99% accuracy on the readings which can help to deliver precise research outcomes. The logger comes up with current and voltage probes to access the energy-related data of a particular setup/machine. The probes provided need to be connected to the power input of the setup. Then, one end of the probes was connected to the milling machine power input while the other end was connected to the logger. Figure 4.2 shows the data logger connection with machine.

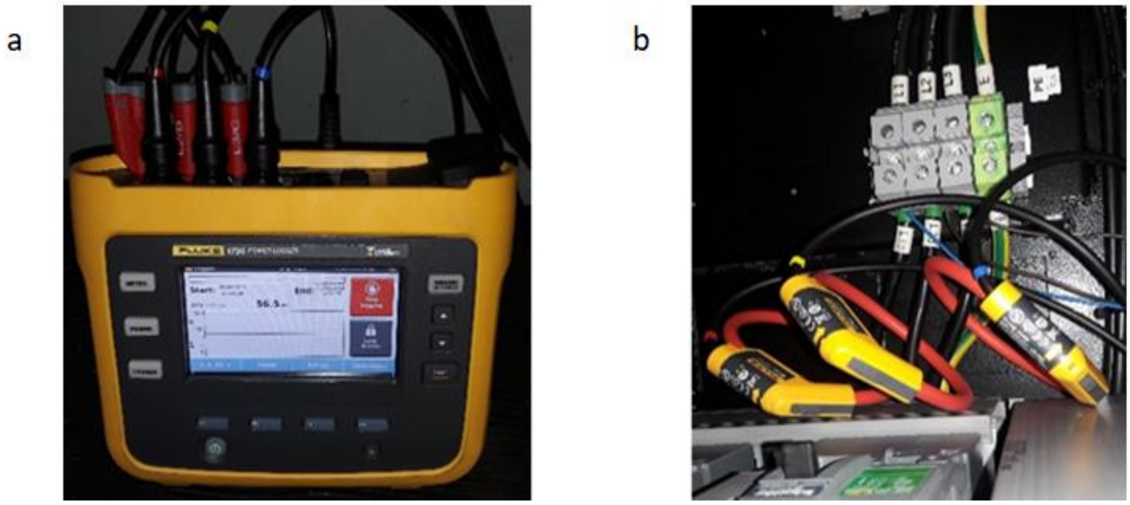

Figure 4.2: (a) Energy data logger connection; (b) Current probe looping at the supply end

Three energy consumption values were taken for each parameter setup, and then the three energy consumption values were averaged to take the most appropriate value for the energy consumption for the considered parameter setup (Experiment number). The results of the energy study are presented in Table 4.1 after subsequent processing of primary energy data.

Table 4.1: Electrical energy inputs

Experiment No.	**Energy consumption of Expt. round 1 (Wh)**	**Energy consumption of Expt. round 2 (Wh)**	**Energy consumption of Expt. round 3 (Wh)**	**Average energy (Wh)**
1	982.57	1096.47	984.62	1,021.22
2	973.11	978.41	975.45	975.66
3	834.06	831.59	824.25	829.97
4	825.23	805.43	804.45	811.71
5	598.03	688.07	569.45	618.52
6	518.74	519.39	525.41	521.18
7	724.17	755.62	751.8	743.86
8	677.05	645.55	676.34	666.32
9	554.64	560.72	542.77	552.71

4.1.2.2 Consumables and releases study

Energy consumption, consumables, and releases are quantified for different parameter combinations. Three experiments were performed for each parameter set and output measures (reference flows) were averaged to improve the accuracy and reduce human error. Then, 27 experiments were conducted and the corresponding reference flows in terms of energy, consumables, and releases were measured. The primary data were exported to MS Excel for subsequent processing and analysis.

Consumables were identified as the workpiece material (Low alloyed steel), tool material (Ferronickel and Ferrochromium), water, and petroleum oil. Since the geometries are the same for all cutting programs, workpiece material removed is estimated the same for all experiments. The gaps/deviations between parameter levels were not made substantial in light of the safety of the tool and the quality of output. As this was a collaborative experiment with an industrial machining centre, the autonomy of the researcher was slightly compromised. Thus, the tool material consumption was estimated to be the same across all experiments. Since the tools are reused, it is assumed the total volume as the usage. Also, it is assumed that the average tool wear figures for all machining cycles by considering the material removal rate and machining time as high material removal rates take less time for machining. It is understood that these assumptions sacrifice the data quality to a certain degree. However, the authors prefer this way than opting for a full theoretical model to calculate tool wear which could largely influence the uncertainty of data. Petroleum oil and water consumption are apportioned by comparing the machining time against their replacement cycles. Therefore, flow rates were traced using the calculations of survey data. The consumables and releases are stated in Table 4.2.

Table 4.2: Consumables and releases

Expt No	Inputs					Outputs	
	Work piece material (g)	Tool material (g)		Water (g)	Oil (g)	Oil to soil (g)	Water to air (g)
		Ferronickel	Ferrochromium				
1	200.35	0.60	0.57	1041.38	34.78	34.78	935.30
2	200.35	0.60	0.57	1022.11	34.13	34.13	917.99
3	200.35	0.60	0.57	813.83	27.18	27.18	730.93
4	200.35	0.60	0.57	836.31	27.93	27.93	751.12
5	200.35	0.60	0.57	678.50	22.66	22.66	609.38
6	200.35	0.60	0.57	596.84	19.98	19.98	536.04
7	200.35	0.60	0.57	836.08	27.91	27.91	750.91
8	200.35	0.60	0.57	1057.43	35.31	35.31	949.71
9	200.35	0.60	0.57	602.81	20.13	20.13	541.39

5. RESULTS AND DISCUSSION

5.1 Life cycle impact assessment

Life cycle impact assessment (LCIA) helps to interpret the environmental impact by environmental impact scores [112], [113]. The analysis is performed using SimaPro version 8. ReCiPe Endpoint (H) LCA method is used for the analysis as it considers both midpoint and endpoint measures of the environmental mechanism [31]. The ascertained energy, consumables, and releases figures were then fed to the SimaPro for subsequent analysis of environmental performance. The analysis has been conducted considering three damage category parameters namely Disability-adjusted life year (DALY), species.yr, and USD2013 followed by human health, ecosystem, and resources respectively. Disability-adjusted life year (DALY) is used as a policy-making tool in a range of countries. DALY states 'Time lived with a disability and the time lost due to premature mortality [114] which can be considered as a more effective parameter to indicate damage. Then, the environmental damage assessment details related to all the experiment setups are tabulated by considering the three damage categories namely human health, ecosystems, and resources as shown in Table 5.1.

Table 5.1: Damage assessment outputs for nine experiment setups

Damage category	**Unit**	**Expt No. 1**	**Expt No. 2**	**Expt No. 3**	**Expt No. 4**	**Expt No. 5**	**Expt No. 6**	**Expt No. 7**	**Expt No. 8**	**Expt No. 9**
Human health	DALY	4.25E-06	4.16E-06	3.77E-06	3.82E-06	3.36E-06	3.22E-06	3.68E-06	3.53E-06	3.28E-06
Ecosystems	species.yr	4.33E-09	4.22E-09	5.06E-09	3.81E-09	4.24E-09	3.1E-09	3.65E-09	3.48E-09	3.18E-09
Resources	USD2013	0.080575	0.07833	0.083525	0.06841	0.06865	0.05229	0.06554	0.06580	0.05370

The data in Table 5.1 has been added to a bar chart to identify the key factors of damage. Then, the outcomes of each of the nine experiments were plotted based on the three damage assessment categories as shown in Figure 5.1.

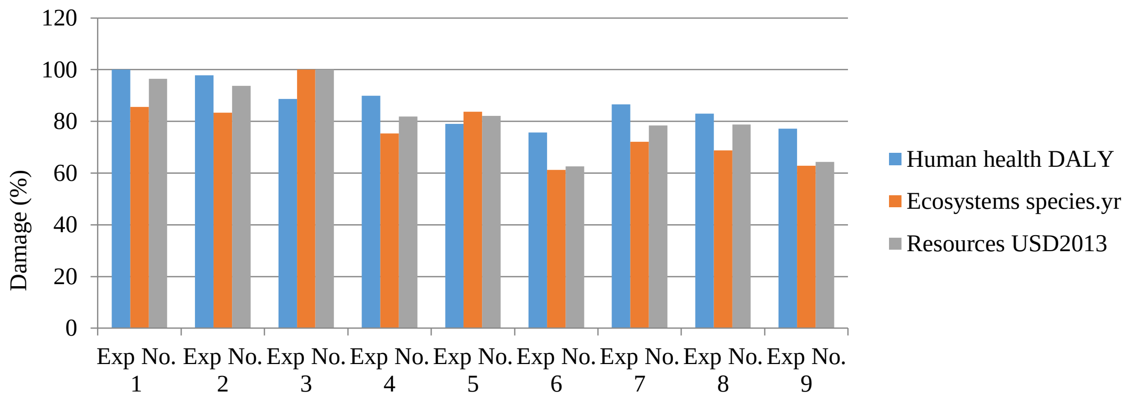

Figure 5.1: Comparison of the impact of nine experiments

According to the bar chart, the highest damage to human health occurs in the first experimental setup while the third setup shows the peaks for ecosystem and resources. The sixth experiment setup has the lowest environmental damage considering all the assessment categories. Referring to Table 5.1 and Figure 5.1, the sixth experimental setup has shown the lowest values for consumables and releases which assured the lowest damage. Thus, the parameters of the sixth experiment setup yield the lowest environmental damage. The parameters are depth of cut, feed rate and rotational speed referring to the five milling operations.

The following tree diagram shows the comparison of environmental impact contributed by its input and outputs. ReCiPe method summarizes the endpoint categories to a unitless figure called Ecopoints [115]. Then the overall contribution to the environmental impact for a specific experiment setup is presented in the diagram indicating the damages in percentages. Figure 5.2 shows the contribution of environmental impact for the machine setup that is practiced in the industrial machining process.

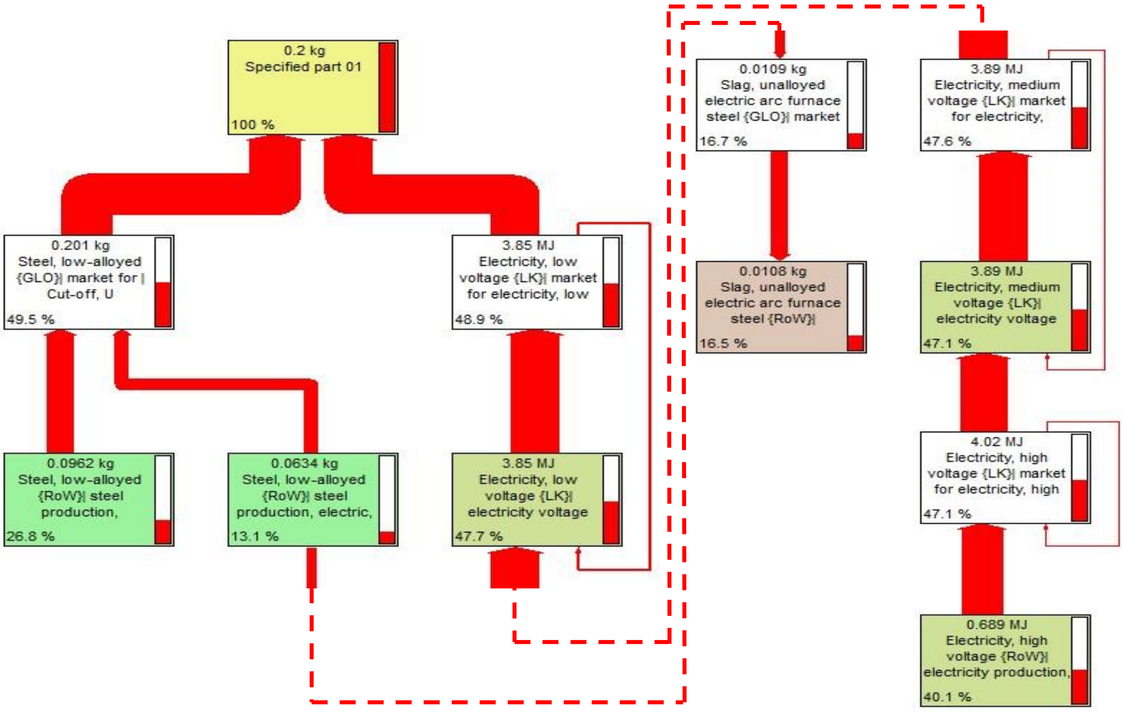

Figure 5.2: Tree diagram showing the composition of environmental impact for industrial parameter setup

Figure 5.2 shows that the majority of environmental damage has occurred from the contribution of workpiece material consumption and energy consumption. The environmental impact of workpiece material consumption has been considered from the production of low alloy steel where the production is represented at the global level. In this study, an average global production is considered to refer to geographical location global (GLO) and Rest-of-the-World (RoW). Further, the study assumed that the factors of global electrical energy consumption inline Sri Lanka (LK) contest. Overall, the contributions from the workpiece material consumption and electrical energy usage are close to each other and have an approximate contribution of 50% for each factor.

Thus, all the other inputs and outputs are only responsible for 1.5%. Since Figure 5.3 is plotted with the consideration of Ecopoints, it is important to have an idea of contributions to each damage assessment category. Then, Figure 5.3 has plotted to identify the environmental damage by considering three damage categories as human health, ecosystems, and resources.

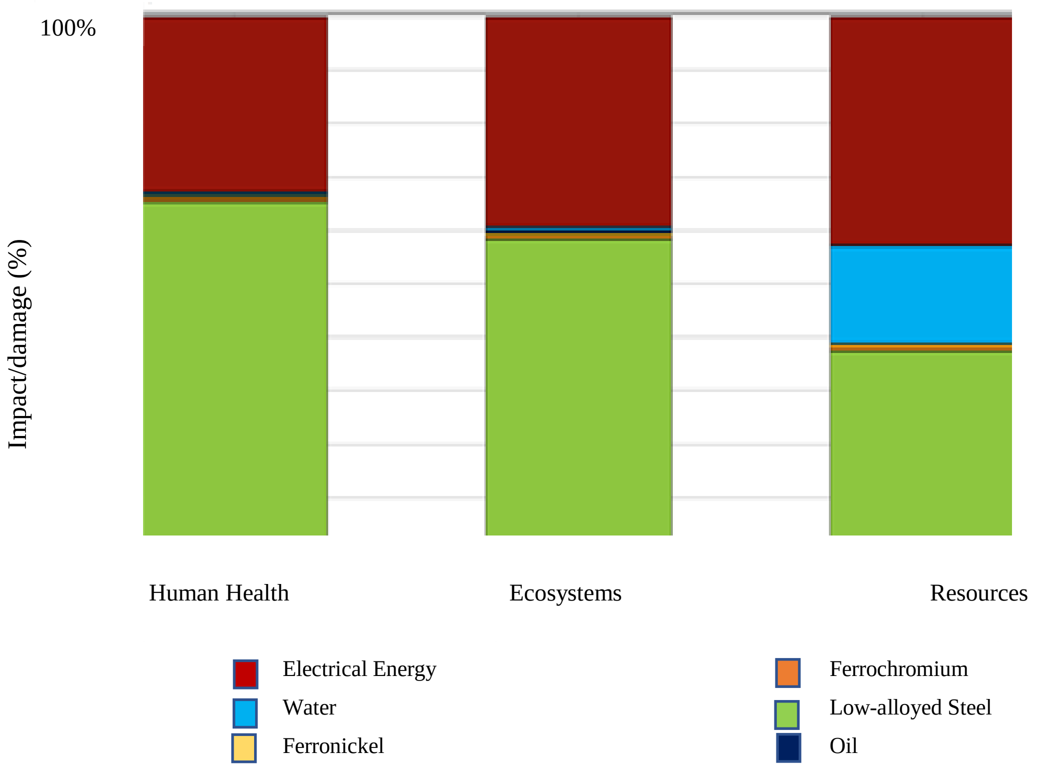

Figure 5.3: Endpoint analysis Impact assessment of industrial parameter setup

According to Figure 5.3, electrical energy consumption and the usage of low-alloyed steel play a major role by making a huge contribution to environmental damage. At the same time, the usage of water has caused considerable damage in terms of resource consumption. The impact of the workpiece material, low-alloyed steel, is over 50% in both Human Health and Ecosystems categories while energy consumption is the major impact factor over resources impact.

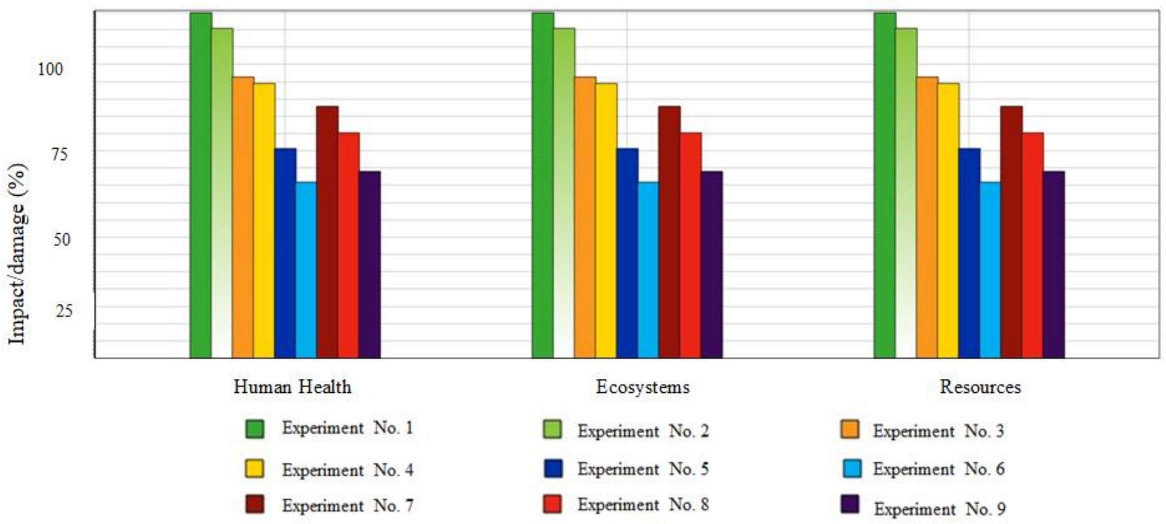

Figure 5.4: Endpoint analysis Impact assessment of nine experiment setups

When the nine cutting scenarios are concerned, a majority of damage happens due to the low alloyed steel and electrical energy consumption while the impact is due to low alloyed steel being constant for all the parameter setups. Then it is important to study the energy consumption related to each experiment setup concerning different damage assessment factors as shown in Figure 5.4.

5.1.1 Parameter setup with low environmental impact

The experiment setup has three machining parameters. Each machining parameter (Depth of cut, feed rate, and rotational speed) is followed by five different machining operations (Rough cut by end milling, finishing by end milling, drilling, end milling of a hole, and reaming). Then one machining parameter is represented by five different values. Therefore, conducting optimization for the research work is complicated, and recording consumables and releases individually is a challenge for a continuous industrial machining operation. Thus, optimization procedure such as an analysis of variance has not been included. This would affect the quality of the results. However, when considering the uncertainties and approximations of the data itself, the effect of the absence of such an optimisation process is believed to be marginal.

Further, the experimental setup has been considered as three main control parameters (Depth of cut, feed rate, and cutting speed) with three levels for each parameter. A parameter setup with the lowest impact has been identified out of the existing parameter combinations to propose for the industrial case. Table 5.2 represents the 6th parameter combination which shows the lowest environmental impact out of nine experiment setups.

Table 5.2: Parameter setup with minimum environmental impact through 9 experiment setups

Expt. No. (*3)	**a. Depth of cut (mm)**					**Feed rate (mm/min)**					**Cutting speed (rpm)**				
	Rc	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**	**Rc**	**Fi**	**Dg**	**Ho**	**Re**
6	7.5	6	2	0.13	9	90	520	82.5	405	65	700	1800	650	3200	250

5.2 Operator's guide for eco-friendly CNC milling machining

Milling machining needs a careful operational handling for better outcomes. Further, machine operator's can make a significant contribution to reduce the environmental impact of machining. Then the study aims an operator's guide focusing on the environmentally friendly shop floor practices for CNC milling machining. Effective use of the milling machine and related resources can reduce the environmental impact. Overall, the guide includes nine sustainable machining practices to be followed to minimize the environmental footprint of milling.

- **Practice maximum possible material removal rates**
- **Use appropriate cooling techniques**
- **Reduce manual controlling of the tool for material removal**
- **Effective and efficient arrangement of non-cutting activities**
- **Select the correct cutting tool**
- **Select the correct machine**
- **Plan and schedule the operations of the milling shop**
- **Use optimized the cutting path**
- **Practice correct disposal methods**

The detailed description of each guideline has elaborated from I to IX.

I. Practice maximum possible material removal rates

Material removal rates (MRR) can be controlled by controlling the machining parameters such as feed rate, axial and radial depth of cut.

Higher feed rates and higher depth of cuts result in a higher MRR where the maximum possible MRR can reduce the environmental footprint caused by milling. Moreover, it is recommended to pay attention to optimized process parameter arrangements for mass production.

II. Use appropriate cooling techniques

Flood cooling, dry machining, minimum quantity lubrication (MQL), cooled air lubrication, and Nanofluid cooling are some current cooling applications in machining. Generally, flood cooling gives a better machining outcome, and dry machining results in the lowest machining performances. Anyhow, flood cooling is liable for high environmental damage whereas dry machining causes less damage.

Thus, an effective and efficient cooling technique is needed to keep better outcomes of both machining performances and environmental impact. Then the guide proposes to use MQL as the best cooling method to practice, which will reduce energy consumption and post-machining disposals while enhancing the machining performances.

III. Reduce manual controlling of the tool for material removal

Operators usually practice manual control of CNC machines for minor and easy metal cuttings. For a manual cut, operators should have a good sight of the cutting edge where machining happens inside a cloud of coolant throughout the machine's door.

Then it is better to practice computer programs for material removals to reduce the damage of both tool and workpiece where a replacement of tool or workpiece causes environmental damage.

IV. Effective and efficient arrangement of non-cutting activities

Non-cutting activities refer to the displacement of the cutting tool including activities such as cutting tool moving and tool changing.

The non-cutting movements should have to be optimized by reducing the extra movements of the tool where the optimized movements should conduct with rapid displacements.

Further, the rotations of the tool magazine need to be kept lower where the order of machining operations needs to be matched with the sequence of the tool arrangement. Overall, the tool path designs with shorter cycle times can yield greater manufacturing and environmental performance.

V. Select the correct cutting tool

The machining quality influences the energy footprint where sharp cutting tools leave a less environmental impact compared to blunt tools. Then it is important to use a sharp cutting tool.

Manufacturing milling tool consumes a bulk of energy whereas frequent replacement of tools withstands a considerable environmental impact. Then reusing of tools by grinding and use of replaceable tool tips can reduce the impact.

Milling machining offers a range of cutting operations. The use of correct cutter geometry for appropriate cutting operations can reduce the environmental impact. Thus, milling cutters manufactured with the required standards are recommended for use.

VI. Select the correct machine

Large machinery consumes a high amount of energy. Then the selection of a milling machine needs to be done focusing on the energy requirement of the job. For example, micro-milling can be performed on a small milling machine which leaves a low environmental impact.

VII. Plan and schedule the operations of the milling shop

Process, product, and hybrid layout are the basic three types of shop floor arrangements. Arrange the shop flow according to the process layout if the product varieties are high. Shop flow arrangements should follow a product layout for mass productions with low varieties. Use cellular layouts for moderate varieties and quantities.

Usually, shop floors come up with process layouts that need effective process planning and scheduling of the machine shops. Use operations sequence and the machining features with machine availability to schedule the machining processes.

Overall, try to reduce the material handling as much as possible.

VIII. Use optimized the cutting path

Overutilization of cutting actions leaves a significant environmental impact due to excess energy consumption. Manual coding of the tool path will result in extra movements of the tool. The guide proposed to use a recommended computer-aided tool to generate the optimum tool path.

IX. Practice correct disposal methods

Disposal of coolants is responsible for eco-toxicity. Recycling cutting fluid is identified as an effective way to reduce the environmental impact of coolant disposal, where performing such work is not practical for machine operators at the shop floor. Then it is recommended to use an eco-friendly cooling technique such as MQL to reduce the cutting fluid disposals.

The disposal of metal chips is responsible for a large environmental impact. Eco-friendly recycling of metal chips can minimize the environmental impact. Thus, recycling metal chips with in the shop floor is not practical. Then it is recommended to direct the metal chips to a sustainable recycling workshop. The operator's need to take actions as much as possible to sort metal chips before they issuing the chips outside where unsorted chips can lead a barrier to the recycling process.

6. CONCLUSION

The purpose of the research was to promote the sustainable manufacturing practices focussing on assessing the environmental performance of milling machining. The literature review aims to identify the contribution of impact factors on environmental damage and to understand the sustainable shop floor practices in milling machining. The literature findings identified a need for sustainable milling machining practices on the shop floor and a requirement to quantify the environmental impact of milling.

The initial objective of the research work is to identify the key contributing factors to the environmental impact of the milling process. The review shows that the contributing factors leave significant environmental damage, where the key contributing factors of environmental impact were identified as energy consumption, material usage, cooling, tool path design, tool design, product design, and machining parameters.

The second objective of the research is to quantify the environmental impact of milling machining. Further, an experiment was designed parallel to an industrial milling operation. The energy consumption was measured using a data logger whereas the consumables and releases were estimated using sensible past data of the machining center. The ISO 14044 life cycle analysis guidelines were used to analyse the environmental performance of milling. The results show that electrical energy consumption and workpiece material usage are the two factors that contribute mostly to the adverse environmental impact while coolant also contributes to a fair impact.

The final objective of the study is to develop an operator guideline for an improved environmental performance of industrial milling operations. Sustainable milling practices were identified through the literature and experiment outcomes. In the end, an operator’s guideline for an improved environmental performance of industrial milling operation has been compiled focusing on the eco-friendly machining practice at the milling machining shops.

6.1 Limitations

In this study, an industrial milling process is monitored which includes a combination of five milling operations. Then, the generalizability of the results is low due to limited controlled experiment setups. Further, an optimization process, such as an analysis of variance, was not used due to the complications of getting full control of an ongoing industrial milling operation. This would affect the quality of the results. However, it is presumed to be marginal when the uncertainties of the raw data quality are considered.

6.2 Contribution to the knowledge and practice

Key parameters of environmental impact are identified and quantified referring to the environmental sustainability of milling machining. An operator's guide has been prepared including a set of shop floor machining practices to generally practice the day-to-day industrial machining operations to be more sustainable in milling.

6.3 Further research areas

Further research could be directed to embed the optimum parameter combinations in CNC machine control systems itself. This will in-built the sustainability aspects even if the operators are not that aware of the sustainability of machining operations.

The operator's guide is developed under the consideration of a specific industrial milling process referring to available literature details. Thus, the guidelines could be validated to match common milling processes.

Cooling and lubrication of milling were separately studied in the review. Then numerous cooling methods were identified in the literature such as dry cutting, flood cooling, minimum quantity lubrication, minimum quantity cooled lubrication, cooled air lubrication, Cryogenic cooling, and Nanofluid lubrication. Within the study of cutting fluids, the use of Nanofluids has shown improved performance on energy footprint. Also, it is found that the use of Nanofluid lubrication in milling is a new area of research and there will be research gaps that are yet to be addressed.

The study identified a requirement for further studies on parameter optimization of milling machining to minimize the environmental impact. It requires a parameter optimization following the environmental impact of each machining operation separately.

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Appendix A: First experiment design

When we are considering the design of experiment, 10 CNC milling machine operators are interviewed from different die and mold centers. At the same time, details from published research are extracting from the literature review to make the design more stabilize.

Surveyed machines were examined from 4 different institutions, such as University of Moratuwa, University of Ruhuna, Kramski Lanka (Pvt) Ltd and Ceylon German tech. Qualitative analysis of survey is conducted to have the first experiment design.

Questionnaire for milling machine operators

Surveyor sheet for machine operators of Hartford LG-1000 CNC milling machine at die and mold center, department of mechanical engineering, University of Moratuwa

1. Usually machining materials (Please specify with the sequence of usage)

   M1: …………………………………

   M2: ………………………………….

   M3: ………………………………….

   M4: ………………………………….

2. Usual spindle speeds for different materials (rpm)

   M1: …………. M2: …………. M3: ………….
   M4: ………….

3. Usual feed rates for different materials (mm/min)

   M1: …………. M2: …………. M3: ………….
   M4: ………….

4. Usual depth of cuts for different materials

   a. Axial depth of cut (mm)

   M1: …………. M2: …………. M3: ………….

   M4: ………….

   b. Radial depth of cut

M1: …………. M2: …………. M3: ………….

M4: ………….

5. Usually used milling cutter(s):

6. Usual milling method(s) (i.e. Side milling, Face milling, Slot milling, etc):

7. Usual cutting status

   ☐ Up milling ☐ Down milling

   Please specify the reasons for answer at question 5(if any):

8. Usual cooling condition

   ☐ High ☐ Medium ☐ Low

9. Usual time taken for refilling the coolant tank:

10. Is there any dry milling performing at machine?

    ☐ Yes ☐ No

    If 'Yes', please specify the work material(s):

11. Machine standby status at not working period:

    a. At holidays (not working days): ☐ Standby ☐ No
    b. At working days: ☐ Standby ☐ No

    If 'Yes' for above 'b.', please specify the usual maximum standby time:

12. Are there any bulk orders of same model? ☐ Yes ☐ No

    If 'Yes',

    Usual size of order (Number of item):

    Rough machining time per item (min):

    Are there any bulk order(s) to be received? When? :

List of machines surveyed

- Hartford LG-1000
- Hartford LG-500
- Deckel Mako-DMU 35M
- Deckel Mako-DMC 60T
- Arix V1000
- DMG Mori
- MIKRON HSM 700
- MIKRON VCE 1000
- Makino f5
- Roder RXP500

Hartford LG-1000 milling machine at die and mold center, department of mechanical engineering, university of Moratuwa will be used to conduct the experiments which has the maximum spindle speed and feed rate as 12000rpm and 3000mm/min respectively.

1. Common material usage
    - Under the survey– Aluminium (pure Al and 1.4365), Steel (1.2379, 1.1730, 1.2085, 1.2380, HRC 52-60, P-20, SW41), Mild steel, Copper, Graphite
    - Under the literature review – Aluminium (AA6061-T6, 7075-T6, A6061P-T651), Steel (EN31, DIN GX40CRMOV5-1, P-20), Mild steel, Cobalt-alloy, metal matrix composites, Inconel 718, Graphite

- Aluminium and steel can be considered as the common materials for both industrial and survey cases. Then Aluminium and Steel are chosen for the experiments.

2. Cutting method- Side milling
3. Cutter selection- Most of the machines use the carbide or HSS end mill cutters with the diameter of 10mm.

Note: Cutting speed is vary with the machine capability for same material: Hartford LG-1000

4. Average cutting speeds from survey

    - Aluminium-3000mm/min
    - Steel-2000mm/min
    - Middle level-2000mm/min (Lower level is taken as middle due to cutter safety)
5. Average depth of cut per run

- Let us take the axial depth as a constant,
    - Aluminium- 0.4mm
    - Steel- 0.2mm
    - Constant axial depth- 0.3mm
- Radial depth is varied taking the average depth as follows,
    - Aluminium- 0.4mm
    - Steel- 0.2mm
    - Middle level of radial depth- 0.2mm

6. Average Feed rates
    - Aluminium- 1800mm/min
    - Steel- 1200mm/min
    - Middle level of feed rate- 1200mm/min
7. Cutting status- Down milling

Experiment design method

Taguchi orthogonal array is used to design the experiment. Then the levels of cutting parameters are assigned according to the literature.

Milling parameters and their levels

Parameter	Level 01	Level 02	Level 03
Cutting speed (mm/min)	1500	2000	2500
Radial depth (mm)	0.2	0.3	0.4
Feed rate (mm/min)	850	1200	1550

The other variable is the material type. Then Aluminium and Steel materials can be considered as the fourth milling parameter.

Experiment arrangement

Experiment No.	Material (A-Aluminium, S-Steel)	Cutting speed (mm/min)	Radial depth of cut (mm)	Feed rate (mm/min)
1	A	1500	0.2	850
2	A	1500	0.3	1200
3	A	1500	0.4	1550
4	A	2000	0.2	1200
5	A	2000	0.3	1550
6	A	2000	0.4	850
7	A	2500	0.2	1550
8	A	2500	0.3	850
9	A	2500	0.4	1200
10	S	1500	0.2	850
11	S	1500	0.3	1200
12	S	1500	0.4	1550
13	S	2000	0.2	1200
14	S	2000	0.3	1550
15	S	2000	0.4	850
16	S	2500	0.2	1550
17	S	2500	0.3	850
18	S	2500	0.4	1200

Appendix B: Sample of questionnaire feedback

Questionnaire for milling machine operators in die and mold centers

1. Operator's name : M. A. U. D. GUNAWARDANA
2. Location/Company : Kromski
3. Machine : MIKRON VCE 1000 pro-x
4. Top materials being used
   - M1: 1.2379
   - M2: 1.2085
   - M3: 1.1730
   - M4: 4365 (Alu)
5. Usual spindle speeds for each of the above material (rpm)
   M1: 5000 M2: 8000 M3: 10000 M4: 15000
6. Typical feed rates for each material (mm/min)
   M1: 300 M2: 400 M3: 500 M4: 1000
7. Typical depths of cuts for each material (for a run)
   a. The axial depth of cut (mm)
   M1: 10 M2: 15 M3: 20 M4: 22
   b. The radial depth of cut (end mill, mm)
   M1: 5 M2: 10 M3: 10 M4: 20
8. Common milling cutter(s) being used (Please specify the tool specifications such as type, tool material, dimensions, tool number, etc.):
   HSS Tools, HM Tools, Carbide tip tool,
   (Tool ϕ 1 - ϕ 20)
9. Usual milling methods (Please give an approximate percentage of usage for each)

Milling method	Side milling	Face Milling	Slot milling	Ramping	Plunge milling
Percentage of usage (%)	75 %	75 %	10 %	10 %	5 %

10. Usual cutting status
    ☐ Up milling ☑ Down milling
    Please specify any reasons for this choice:
11. Is there any dry milling performed?
    ☑ Yes ☐ No
    If 'Yes', please specify the work material(s):
12. Coolant pump details
    a. Power (kW) : (3.3 / 3.8 kw)
    b. Maximum flow rate : 300 l
    c. Is it possible to control the flow rate of the coolant pump?
    ☑ Yes ☐ No
    If 'Yes', specify the rang of flow rate:

13. Disposal of used coolant
How often : Auto
Average disposal volume: 800 l
Please specify the disposal method of used coolant:
To destrey another insitiution
14. Refilling of the coolant due to evaporation (without a direct disposal)
How often :
Average top-up volume : 8 l for week
15. Please specify the disposal method of metal chips:
Given to Recycle
16. Machine standby status at non-working period:
a. At holidays (non-working days): ☐ Standby ☐ On ☑ Off
b. At Nights: ☑ Standby ☑ On ☐ Off
c. Average machining hours per day:
17. Are there any bulk orders of same model? ☑ Yes ☑ No

If 'Yes',
Usual size of order (Number of item):
Rough machining time per item (min):
Are there any bulk order(s) to be received? When? :
18. Power consumption of auxiliary components (Please specify if any other)
a. Chiller (kW) :
b. Drivers (kW) :
c. ……………… :
d. ……………… :
e. ……………… :

Appendix C: Training program _ GHG assertion

Completion of a training program of ‘Consultant development in GHG assertion’ under the fund allocation of Senate Research Committee grant (SRC/CAP/2018/04).


Sri Lanka

CERTIFICATE

This Certificate is presented to

K.P.MANOJ PRIYANKARA

for successfully completing

the

Two-days Training Programme

on

“Consultant Development in GHG Assertion

(Carbon Footprint Calculation) ”

Based on ISO 14064-1, 2, 3 & ISO 14067 Standards

organized by

National Cleaner Production Centre, Sri Lanka

14th & 15th August 2018

Colombo, Sri Lanka

Samantha Kumarasena

Chief Executive Officer

NCPC Sri Lanka

RECPnet

Member of UNIDO-UNEP Global Network on Resource Efficiency and Cleaner Production (RECP-Net)

Appendix D: Calculations for final experiment design

The work piece material is EN3D which is also known as Bright Steel. The calculations are done by considering five tool changes. The five tool changes and their specifications are added in the following table.

Table: Tool specifications

Cutting operation	Tool material	Tool diameter (mm)
Rough cutting (RC)	HSS-Co	15
Finishing (F)	Solid carbide	14
Drilling (D)	HSS-Co	7
End milling (EM)	HSS-Co	6
Reaming (R)	Solid carbide	8

Note: Standard tool specifications are considered for the calculations.
Equations for cutting speed and feed rate can consider as follows,

$$V = \frac{\pi D N}{1000} \; where \; N_1 = \frac{V_1 \times 1000}{\pi D}$$

$$V_f = N f_z Z$$

Where,

V – Cutting Speed (Surface)/m/min

D – Diameter (mm)

N – rotational speed (rpm)

V_f – Feed Rate (mm/min)

f_z – Feed per tooth

Z – No of tooth

01. <u>Considering the rough cut</u>

$V = V_1 = 36\, m/min$
$D = D_1 = 15\, mm$
$N = N_1$
$V_f = V_{f1}$
$Z = Z_1$
$f_z = f_{z1}$
Feed No = 6

$$N_1 = \frac{V_1 \times 1000}{\pi D}$$

$$N_1 = \frac{36 \times 1000}{\pi \times 15}$$

$N_1 = 763.94$

$\underline{\underline{N_1 \cong 764\, rpm}}$

f_{z1} = 0.04275

$V_{f1} = N_1 \times f_{z1} \times Z_1$

$= 764 \times 0.04275 \times 4$

$= 130.644\, mm/min$

Depth of cut = $0.5D_1$

= $0.5 \times 15\, mm$

= $\underline{\underline{7.5 \text{ mm}}}$

02. <u>Considering the finishing cut</u>

$V_{finish} = V_2 = 70\, m/min$

$D_2 = 14\, mm$

$N_f = N_2$

V_{f2}

Z_2

f_{z2}

Feed No = 8

$$N_2 = \frac{V_2 \times 1000}{\pi D}$$

$$N_2 = \frac{70 \times 1000}{\pi \times 14}$$

$N_2 = 1591.55$

$N_2 \cong 1592\, rpm$

<u>Feed Rate</u>

Feed No = 8

f_{z2} = 0.0535

$V_{f2} = N_2 \times f_{z2} \times Z_2$

$V_{f2} = 1592 \times 0.0535 \times 4$

$V_{f2} = 340.685\ mm/min$

$V_{f1} \cong 341\ mm/min$

Axial Depth of cut = $1.5D_2$

= $1.5 \times 14\ mm$

= 21 mm

03. Considering the Drilling

Speed (V) = 100 ft/min

= 30.48 m/min

$$N = \frac{1000\ V}{\pi D}$$

$$N = \frac{1000 \times 30.48}{\pi \times 7}$$

$N = 1386.01$

$N \cong 1386\ rpm$

X = 0.1016 mm/rev

Feed rate = X × N

= 0.1016 × 1386

= 140.81

$\cong 140\ mm/min$

04. Considering the end milling operation

$$N = \frac{1000\ V}{\pi\ D}$$

$$N = \frac{1000 \times 40}{\pi \times 6}$$

$N = 2122.065$

N = 2122 rpm

Feed = 0.013 mm/tooth

$V_f = W f_z Z$

$V_f = 2122 \times 0.013 \times 4$

$= 110.344$

$\underline{\underline{\cong 110\ mm/min}}$

Radial Depth = 0.1$\times D$

= 0.1×6

= <u>0.6 mm</u> > 0.13 acceptable

Axial Depth = 1.5 D

= $1.5 \times 6mm$

= 9 mm

05. <u>Considering the reaming operation</u>

V = 38 m/min

Feed = 0.11 mm/rev

$$N = \frac{V \times 1000}{\pi D}$$

$$N = \frac{38 \times 1000}{\pi \times 8}$$

$$N = 1511.97$$

$\underline{\underline{N \cong 1512\ rpm}}$

Take feed as 0.076 mm/rev

Feed Rate = $0.076\ mm/rev \times 1512 rev/min$

= 114.91 mm/min

= <u>115 mm/min</u>

Appendix E: sample CNC program (considering the expt. number 5)

```
%
O1000 (CLAP SYSTEM_MILLING)
(COMPENSATION-WEAR)
(REV-0.70)
(JAN-17-2019-12:43:28PM)

(TOOL 2 - DIA 15.)
(TOOL 3 - DIA 12.)
(TOOL 4 - DIA 7.)
(TOOL 5 - DIA 6.)
(TOOL 6 - DIA 8.)

N1 G90 G17 G40 G80 G00
G28 G91 Z0
T2 M6()
(F-contour)
G00 G54 G90 X-75. Y0. S732 M03
G43 H2 Z50. M08
M08
Z10.
Z2.
G01 Z-7.5 F50.
X75. F130.
Z-15. F50.
X-75. F130.
Z-22.5 F50.
X75. F130.
Z-30. F50.
X-75. F130.
Z-37.5 F50.
X75. F130.
Z-45. F50.
X-75. F130.
Z-46. F50.
X75. F130.
G00 Z10.
M09
M09
M05
G28 G91 Z0
M01

N2 G90 G17 G40 G80 G00
T3 M6()
(F-contour1)
G00 G54 G90 X-73.3 Y3. S1696 M03
G43 H3 Z50. M08
M08
Z10.
Z2.
G01 Z-6. F50.
X73.3 F340.
Z-12. F50.
X-73.3 F340.
Z-18. F50.
X73.3 F340.
```

```
Z-24. F50.
X-73.3 F340.
Z-30. F50.
X73.3 F340.
Z-36. F50.
X-73.3 F340.
Z-42. F50.
X73.3 F340.
Z-46. F50.
X-73.3 F340.
G00 Z10.
X73.3 Y-3.
Z2.
G01 Z-6. F50.
X-73.3 F340.
Z-12. F50.
X73.3 F340.
Z-18. F50.
X-73.3 F340.
Z-24. F50.
X73.3 F340.
Z-30. F50.
X-73.3 F340.
Z-36. F50.
X73.3 F340.
Z-42. F50.
X-73.3 F340.
Z-46. F50.
X73.3 F340.
G00 Z10.
M09
M09
M05
G28 G91 Z0
M01

N3 G90 G17 G40 G80 G00
T4 M6()
(D-drill6)
G00 G54 G90 X-43.6912 Y0. S600 M03
G43 H4 Z50.
Z10.M08
G98 G81 X-43.6912 Y0. Z-47. R-44. F10.
X-10.2337
X23.2238
X56.6813
G80
(D-drill7)
M08
M08
S1018
Z10.
G98 G83 X-43.6912 Y0. Z-57. R-44. Q2. F140.
X-10.2337
X23.2238
X56.6813
G80
M09
M09
M05
G28 G91 Z0
```

M01

N4 G90 G17 G40 G80 G00

T5 M6()

(F-contour2)

G00 G54 G90 X-42.7359 Y0.2921 S2661 M03

G43 H5 Z50. M08

M08

Z10.

Z-50.

G01 Z-52. F50.

G41 D5 X-39.866 Y1.1695 F110.

G03 X-39.866 Y1.1695 Z-52.13 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.26 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.39 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.52 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.65 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.78 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-52.91 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.04 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.17 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.3 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.43 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.56 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.69 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.82 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-53.95 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.08 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.21 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.34 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.47 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.6 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.73 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.86 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-54.99 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.12 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.25 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.38 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.51 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.64 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.77 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-55.9 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.03 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.16 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.29 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.42 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.55 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.68 I-3.8252 J-1.1695

X-39.866 Y1.1695 Z-56.7 I-3.8252 J-1.1695

X-39.866 Y1.1695 I-3.8252 J-1.1695

G01 G40 X-42.7359 Y0.2921

G00 Z10.

X-9.2784

Z-50.

G01 Z-52. F50.

G41 D5 X-6.4085 Y1.1695 F110.

G03 X-6.4085 Y1.1695 Z-52.13 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.26 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.39 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.52 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.65 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.78 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-52.91 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.04 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.17 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.3 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.43 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.56 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.69 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.82 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-53.95 I-3.8252 J-1.1695

X-6.4085 Y1.1695 Z-54.08 I-3.8252 J-1.1695

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X-6.4085 Y1.1695 Z-54.99 I-3.8252 J-1.1695

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G00 Z10.

X24.1791

Z-50.

G01 Z-52. F50.

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X27.049 Y1.1695 Z-56.03 I-3.8252 J-1.1695

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X27.049 Y1.1695 Z-56.7 I-3.8252 J-1.1695

X27.049 Y1.1695 I-3.8252 J-1.1695

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G00 Z10.

X57.6366

Z-50.

G01 Z-52. F50.

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X60.5065 Y1.1695 Z-56.7 I-3.8252 J-1.1695
X60.5065 Y1.1695 I-3.8252 J-1.1695
G01 G40 X57.6366 Y0.2921
G00 Z10.
M09
M09
M05
G28 G91 Z0
M01

N5 G90 G17 G40 G80 G00
T6 M6()
(D-drill5)
G00 G54 G90 X-43.6912 Y0. S881 M03
G43 H6 Z50. M08
M08
Z10.
G98 G81 X-43.6912 Y0. Z-55. R-44. F115.
X-10.2337
X23.2238
X56.6813
G80
M09
M09
M05
G00 G28 G91 Z0
G90
M30
%
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Appendix F: Specifications for three phase current data logger

The three phase current data logger is acquired by processing the following specification sheet. This specification sheet is developed by considering high end data loggers which were available at the market. Finally, we could able to purchase a Fluke data logger which is usually considered as a quality product.

Specification	**Minimum requirements**
Measurement and functions	The device should be capable of measuring three-phase and single-phase Power, Energy, Voltage, Current, Frequency, Power factor, Active power, Reactive power, Active energy, Reactive energy, Unbalance rate, Voltage and current harmonics.
Data acquisition circuit types	1- phase, split phase, 3- phase delta, 3- phase wye, 3- phase wye balanced, 3- phase (2-element delta), 3- phase delta open leg or more circuit types
Number of voltage/current inputs (input probes)	4 (3 phases and neutral)
Data transfer methods	USB, Bluetooth and Wi-Fi (all three forms)
Sample rate	10 kHz or more
Accuracy	± 1% of reading or better
Memory	‘Flash’ memory should facilitate. Memory should be capable for kept more than a year of data logging with one minute or lesser time intervals.
Measurement technique	Auto-ranging
Current range	5A to 5000A (If more than one probes are needed to capture the specified current range then supply additional probes accordingly)
Maximum current resolution	1A or less
Voltage range	0-1000V
Maximum voltage resolution	0.1V or less
Battery	Rechargeable and replaceable
Battery type	Li-ion or better technology
Battery life	4 hours or more
Charging time	6 hours or less to fully charge
Required power supply	Compatible to 230V (50Hz/60Hz) AC wall socket
Warranty	Instrument and power supply: Two-years comprehensive or more Accessories: one-year or more
Data safety	All data should be automatically logged and kept in the device memory even without power until purposely deleted by the user.
Software	User interface must be in English. Automatic connectivity with Microsoft Windows operating system. Software should facilitate viewing, sorting, analysing and reporting functions. Software should further facilitate conversion of data formats to be read in Microsoft excel and other spread sheet software.
Operating temperature	10 °C to 50 °C or wider range
Display of the device	Colour, touch, graphical display with 100 ppi or more resolution.
Maximum resolution of	0.1% or less

unbalance identification	
Device efficiency	60% or more
Harmonic measurements	Up to 50^{th} harmonic or better

Appendix G: Accepted abstract of 18th Global Conference of Sustainable Manufacturing – 2022

New research has started to focus Nanofluid lubrication over milling. Thus, the new research idea has generated under the further studies of current research work. A literature review on the new topic is going on as an initiation. A full paper research publication is targeting as the third publication. The following abstract is submitted (19th March 2022) to the 18th Global Conference of Sustainable Manufacturing (GCSM 2022). The abstract has been accepted.

Further details

Sustainable machining: A review on the impact of Nano-Coolant over milling machining - Abstract submitted (*22nd of March 2022*) to '18th Global Conference of Sustainable Manufacturing (GCSM 2022)', Berlin, Germany, will be published at ***Springer*** if the full paper get accepted. *(Authors: M. Kurukulasuriya, J. Gamage)*

Sustainable machining: A review on the impact of Nano-Coolant over milling machining

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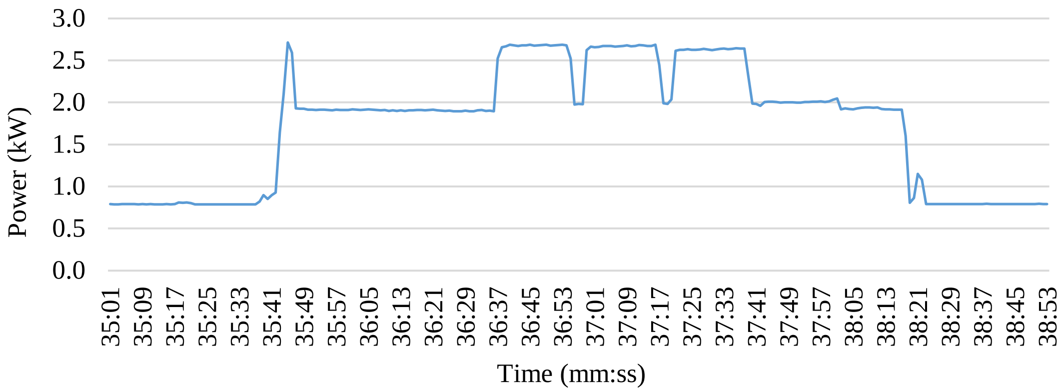
Abstract. Machining significantly contributes to manufacturing. Numerous attempts have been made to enhance the efficiency and the effectiveness of conventional machining including optimization of control parameters, use of efficient tool paths and tools, and effective utilization of coolant. Nano-coolant is a nano-fluid that improves the coolant properties by the addition of ultrafine Nanoparticles to the base coolant. This review aims to identify the changes in the performance of milling machining with the application of a nano-coolant and its contribution to reducing the environmental impact of machining. It is revealed that the nano-coolant can reduce the power consumption and the working temperature while improving the surface quality and the tool life. Further research is required to identify the effects of nano cooling on surface topography in Computer Numerical Control (CNC) milling applications.

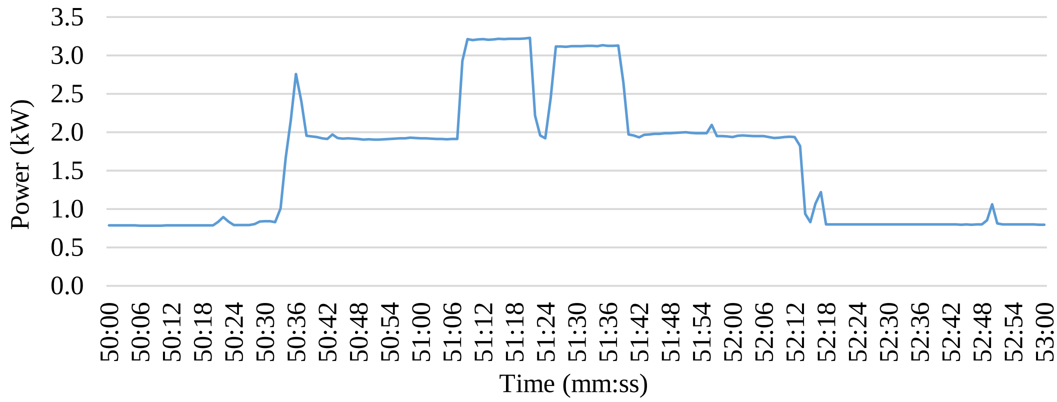
Keywords: Nano-Coolant, Milling Machining, Environmental Impact

Appendix H: Patterns of power consumption during milling operations

Experiment number 01



Experiment number 02



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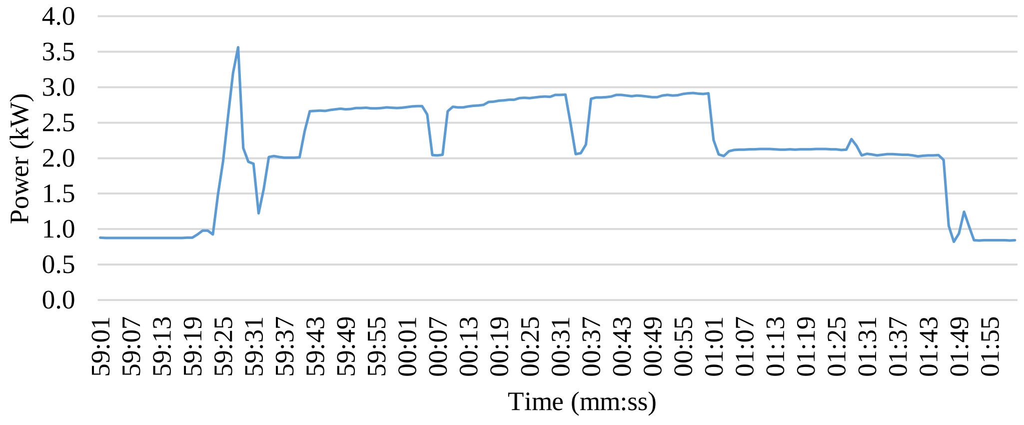

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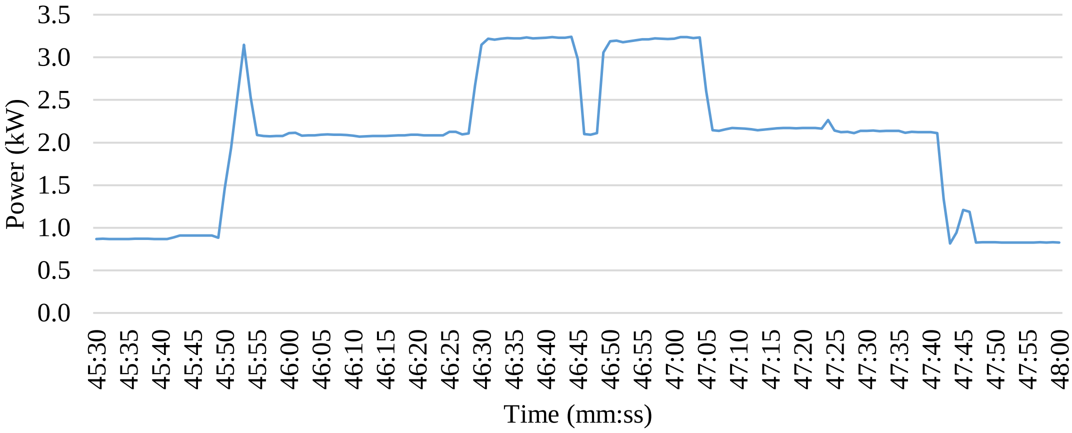

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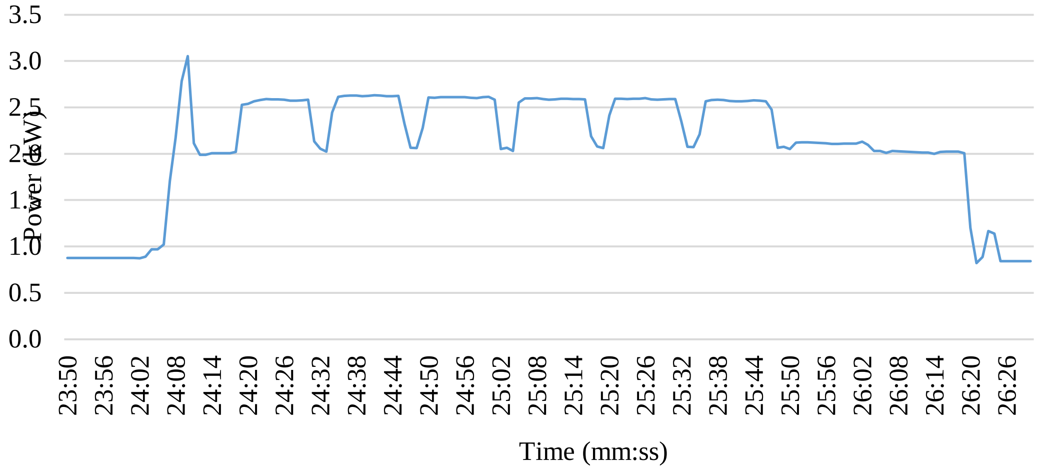

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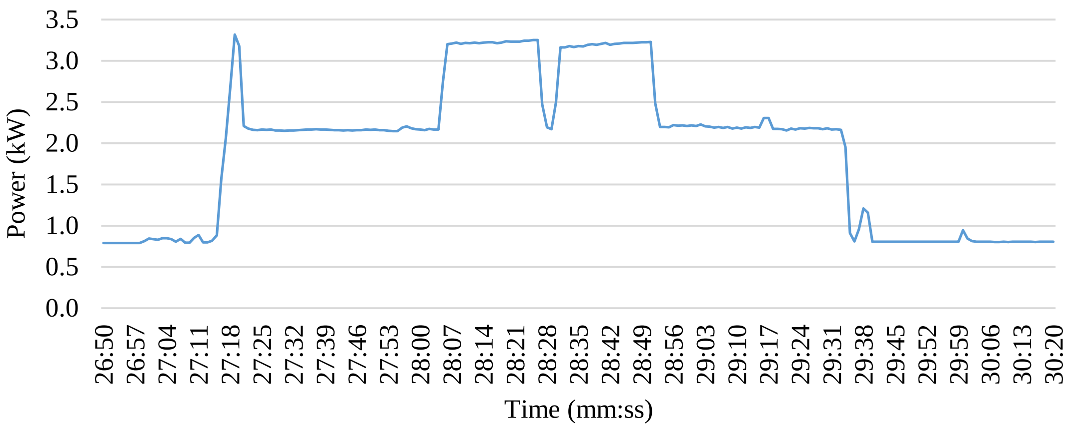

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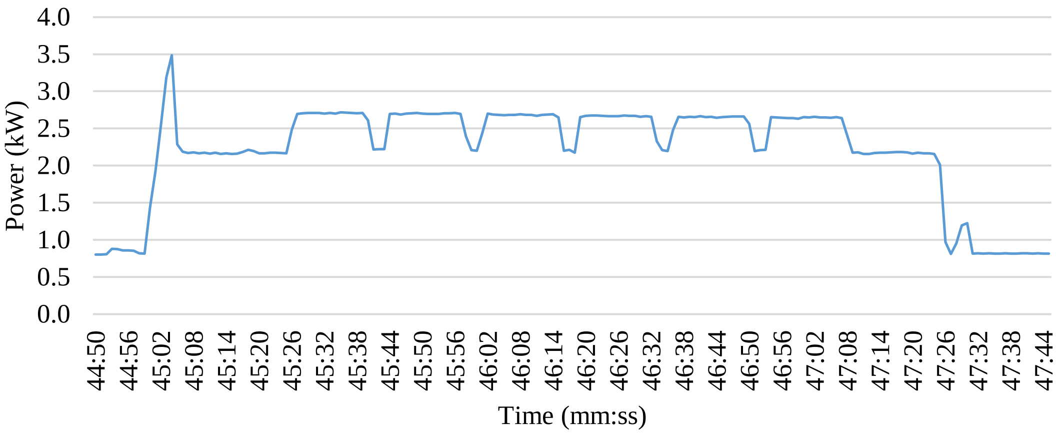

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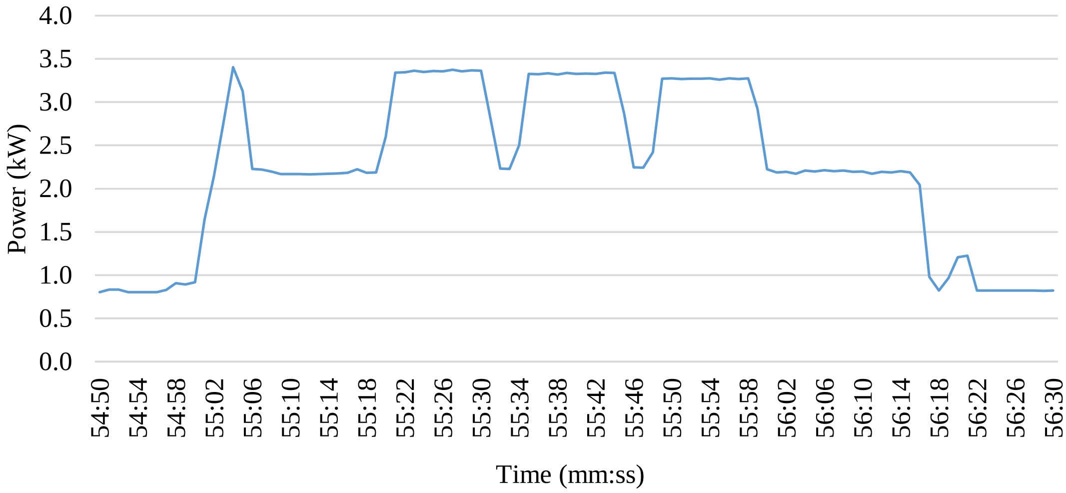

Experiment number 09