OPTIMISING THE OPERATIONAL PARAMETERS AND CONDITIONS TO ENHANCE THE ENVIRONMENTAL SUSTAINABILITY OF TURNING OPERATION

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science by Research in Engineering

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DECLARATION

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Name of the supervisor: Dr. J. R. Gamage

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Signature of the supervisor: Date:

ABSTRACT

The manufacturing sector accounts for nearly 40% and 25% of global energy and resources consumption respectively. The die and mould manufacturing (DMM) sector, contributes largely to the energy and resource consumption in emerging economies. Turning is a popular and essential mode of machining within this sector. Furthermore, operational energy usage and metalworking fluid (MWF) consumption of turning have been identified as the key sources of environmental impacts in this process. However, there is a lack of evidence on analysing environmental impacts of lathe operations in the DMM sector compared to milling operation. Therefore, the purpose of this study is to identify and analyse the life cycle environmental impacts of the commercial turning operation. A series of case studies was conducted in DMM centres to explore the state-of-the-art industrial turning operation. Then, a set of experiments was designed using the Taguchi L_9 method, considering the mostly used workpiece material, cooling condition and cutting parameters. Experiments were performed to evaluate the energy consumption, metalworking fluid (MWF) consumption, surface roughness and material removal rate during turning of AISI P20 with both wet and dry machining. A life cycle assessment (LCA) was performed using SimaPro LCA software with Ecoinvent database version 8.5 to assess the environmental performance of turning. A multi-response optimisation was performed using Grey-based Taguchi method to identify the optimum operating conditions. The results show that turning with wet machining yields better machining and environmental performances compared to dry machining. The largest portion of the energy is consumed for non-productive operations. The LCA results reveals electrical energy as the highest contributor under most of the impact categories. The workpiece material, AISI P20 and cutting insert material show significant contributions to aquatic ecosystems and resource consumption. However, the contribution of MWF on the midpoint impact categories is negligible. Further, the research presents optimum turning parameters to obtain better machining performances while maintaining lower environmental footprint in the context of turning of AISI P20 with wet machining.

Keywords: Sustainable machining, Life cycle assessment, Environmental impact, Turning operation

DEDICATION

I dedicate this thesis to my loving father, *Roy Antony Fernando*, and my mother, *Mary Juliet Kostha*, who guided me always to this achievement. Furthermore, I would like to dedicate this to my elder brothers, *Prasanna Fernando* and *Chamley Fernando*, who supported me to make this work success. Finally, I would like to dedicate this to my loving husband, *Anton Rexi Croos*, for staying with me all the time and encouraged me to this achievement.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
AC	Air Conditioning
ADP	Abiotic Depletion Potential
AISI	American Iron and Steel Institute
Al_2O_3	Aluminium Oxide
ANOVA	Analysis of variance
AP	Acidification Potential
BOD	Biological Oxygen Demand
CC	Climate change
CFC	Chlorofluorocarbon
CH_4	Methane
Cl	Chlorine
CNC	Computer Numerical Control
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
COVID-19	Coronavirus Disease 2019
CT	Confirmation Test
CV	Coefficient of Variation
CVD	Chemical Vapour Deposition
DCB	Dichlorobenzene
DMM	Die and Mould Manufacturing
DOC	Dissolved Organic Carbon
DOE	Design of Experiments
FAEP	Freshwater Aquatic Toxicity Potential
FD	Fossil resource scarcity
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
GRG	Grey Relational Grade

GWP	Global Warming Potential
H_3BO_3	Boric Acid
HPJAM	High Pressure Jet Assisted Machining
HTc	Human toxicity: cancer
HTnc	Human toxicity: non-cancer
HTP	Human Toxicity Potential
IR	Ionising radiation
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LN_2	Liquid Nitrogen
LO	Land use
MDL	Modified Digital Logic
ME	Marine eutrophication
MET	Marine ecotoxicity
MoS_2	Molybdenum Disulphide
MQL	Minimum Quantity Lubrication
MRD	Mineral resource scarcity
MRR	Material Removal Rate
MWF	Metalworking Fluid
N_2O	Dinitrogen Monoxide
Na	Sodium
NH_3	Ammonia
NH_4	Ammonium Carbonate
NIOSH	National Institute of Occupational Safety and Health
NMVOC	Non Methane Volatile Organic Carbon compound
NO_3	Nitrate
NO_x	Nitrogen Oxides
OD	Ozone depletion

ODP	Stratospheric ozone depletion potential
OECD	Organization for Economic Co-operation and Development
PAH	Polycyclic Aromatic Hydrocarbons
PCBN	Polycrystalline Cubic Boron Nitride
PM	Particulate Matter
PMF	Fine particulate matter formation
PO_4	Phosphate
POFE	Photochemical oxidant formation: Terrestrial ecosystems
POFH	Photochemical oxidant formation: Human health
PROSA	Product Sustainability Assessment
PVD	Physical Vapour Deposition
Ra	Arithmetical mean surface roughness
RSM	Response Surface Methodology
SD	Standard Deviation
SEM	Standard Error of the Mean
SLCA	Social Life Cycle Assessment
SO_2	Sulphur Dioxide
TA	Terrestrial acidification
TET	Terrestrial ecotoxicity
Ti	Titanium
TiAlN	Titanium Aluminium Nitride
TiCN	Titanium Carbon Nitride
TiN	Titanium Nitride
TOC	Total Organic Carbon
USA	United States of America
WC	Tungsten Carbide
WD	Water use

LIST OF NOMENCLATURE

Symbol	**Definition**	**Units**
a_p	Depth of cut	mm
E	Energy consumption	kWh
E_{ac}	Energy consumption by air conditioning system	kWh
E_c	Cutting Energy	kWh
E_{co}	Changeover Energy	kWh
E_l	Energy consumption by lights	kWh
E_m	Machining Energy	kWh
E_{nm}	Non-machining Energy	kWh
E_{total}	Total Energy	kWh
ε	Distinguishing coefficient	
f	Feed rate	mm/rev
i	Operating condition	
j	Responses	
k	Total number of responses	
MWF_c	MWF Consumption	ml
n	Spindle speed	rev/min
N	Possible decisions	
η	Signal to noise ratio	
t	Time	
t_c	Cutting Time	s
t_{co}	Changeover Time	s
t_m	Machining Time	s
t_{nm}	Non-machining Time	s
V_c	Cutting speed	m/min
Z_{ij}	Normalized signal to noise ratio	
α	Weighting factor	
γ_{ij}	Grey relation coefficient	
Δ_i	Deviation sequences	
$\overline{\gamma_i}$	Grey relational grade	

CHAPTER 1 INTRODUCTION

This chapter describes the background of sustainable manufacturing and introduces the need of implementation of sustainable machining in Sri Lankan die and mould manufacturing sector. Further, it consists of the aim and objectives of this research. Finally, it describes the structure of the thesis.

1.1 Background

Sustainable manufacturing is a concept of creating products through economically and ecologically sound processes that diminish adverse effects on the environment while conserving energy and natural resources [1]. The industry sector has contributed to over 50% of the global energy utilization in 2018. Further, it is predicted that global industrial energy consumption increases by over 30% within the next 30 years. When considering regions, the non-OECD countries use around 67% of global industrial energy. It has been identified that Asia is the highest energy consumer among non-OECD regions [2]. In 2016, the industrial energy consumption amounts to 30% of the total energy usage in Sri Lanka [3]. The manufacturing sector consumes around 40% of global energy consumption. It is more than 80% of global industrial energy use, making it the largest energy consumer within the sector [2]. Out of that, the machining processes such as turning, milling, grinding, reaming and, etc. contribute to a significant fraction of the energy use [4]. Moreover, the utilization of resources by the manufacturing sector represents approximately 25% of the global resource consumption [5]. Even with the above-mentioned significant energy and resource utilization within the industrial sector, very few studies have focused on improving the sustainability of these practices.

The manufacturing segment, which plays a major role in the industrial economy [6]. Therefore it is necessary to be sustainable to produce more sustainable products and ultimately make the consumers' lives standard. Besides that, the need of reaching completely sustainable is become increasing due to consumer willingness for sustainable products and tougher rules and regulations regarding the environment, health and safety of the consumers' [1]. The number of regulations related to the environment has been established by the European Government; Packaging and

Packaging Waste (PPW 2004), Restriction of the use of certain Hazardous Substance in Electrical and Electronic Equipment (RoHS 2003), Waste Electrical and Electronic Equipment (WEEE 2003), Eco-Design Requirements for Energy Using Products (EUP 2005) [7]. Furthermore, the requirement of labourers in industries for a healthy and pleasant environment for work may also lead to the implementation of "green" concept in machining centres. The concept of green is the process of manufacturing products which use a lower amount of resources while managing worker healthy and friendly environment [8]. The problems relate to the environment are initiated as a result of natural resources utilization and due to the toxic compounds which are added to the environment within the life cycle of different industrial products. Then it leads to strict regulations relating to the environment on industries. Achieving sustainability in production may cause effective improvement in all environment, economic and social areas [9], [10], [11].

The manufacturing sector uses various processes and, machining is used mostly [12]. Moreover, machining is the highest power-consuming process in the manufacturing sector and it is the material removing process or cutting of materials using different cutting tools [4], [13]. The turning operation is used mostly among other machining operations, which removes the material from a rotating/cylindrical workpiece, is the most prevalently used and significant machining technique [14], [15].

1.2 Motivation

The developed countries are greatly aware of the sustainable manufacturing concept and its advantages. Hence, their motivation for implementation practices of sustainable manufacturing is very high. However, when considering the manufacturing industries in developing countries, few of them have tried to implement the sustainability concept inside their working environment, based on the awareness and knowledge which they have been received through their international business colleagues. The reason behind that is the necessity to survive under the pressure coming from the foreign customers who know about the environmental effect of the different processes. But, most of the organizations, try to implement the concept of sustainability not for considering improvements in the environment, social and economic but to gain their reputation through obtaining different awards. The poor attitude behind the sustainability concept was identified as the next biggest barrier of implementing it. Besides that, higher taxes, less awareness of customers about sustainable products and difficulties during maintaining and operating are the other barriers. Furthermore, due to the absence of strict rules and regulations relates to the environment, most of the manufacturing companies not willing to even pay their attention to this subject. Therefore it is difficult to get financial support from banks to implement sustainable manufacturing concept [16].

The energy and MWF consumption during machining are the key factors of its environmental footprint [17]. The die and mould manufacturing (DMM) sector contributes largely in emerging economies, because it represents a crucial phase of a mass-produced discrete parts production [18]. Machining is one of the key operations that is being used in core and cavity production [19]. Milling and electro-discharge machining (EDM) are mostly used for machining dies with more deep cavities [18]. The turning operation is also used to produce some components of dies like guide pins. Many studies have been performed to identify the environmental impact of the milling operation. Kurukulasuriya et al [20] have shown that majority of environmental impacts created by the milling operation in die and mould manufacturing (DMM) sector is due to the electrical energy consumption (more than 30%) and workpiece material (more than 30%). However, there is a lack of evidence in the literature on studies focusing on energy and resource usage of lathe operations in the die and mould sector. Furthermore, there is a research gap of evaluation of the contribution of different inputs on the environmental impact during turning operation and the effect of process parameters on the environmental impact. If these parameters are identified, better operational practices can be developed considering holistic environmental performance instead of focusing on a single operational phase. Therefore, the scope of this study is to bridge the aforementioned research gap of environmental performance analysis of turning operation.

1.3 Aim and objectives

1.3.1 Aim

Identify and analyse the life cycle environmental impacts of the commercial turning operation.

1.3.2 Objectives

- To identify the main factors which affect the environment during turning operation.
- To identify the relationship between machining performances and environmental impact.
- To identify the effect of change of process parameters on the environmental impact.
- To analyse and compare the environmental impact of industrial turning operation with the optimized operation.

1.4 Structure of the thesis

The first chapter describes the background and need of sustainable manufacturing for the industry sector, the motivation of this research work and research aim and objectives. Finally, it describes the overview of this thesis.

The literature review is presented in Chapter 2. At first, it describes the importance of sustainable manufacturing in this industrialised world. Then it explains the analysed literature about sources of the environmental impact of turning operation and identified strategies to reduce them. After that, it describes the best strategy to mitigate environmental impact. Finally, it explains the state-of-the-art of Sri Lankan die and mould sector and, identified research gap.

Chapter 3 describes the methodology of this research. At first, it introduces the mapping of research objectives with data collection methods. Then it describes the detailed methodologies of literature review, background study and experimental study.

Analysis of research data is explained in Chapter 4. First, it describes the analysis of the literature review using Microsoft Excel software. Then it explains the analysis of the interview replies of background study using the Modified Digital Logic (MDL) method. Next, it presents the experimental data analysis using Microsoft Excel software. After that, it gives a detailed description of environmental performance analysis using life cycle assessment (LCA) methodology. Finally, the multi-response optimisation using Grey-based Taguchi method is described.

Chapter 5 consists of the results and discussion of the background study, experimental study, environmental performance analysis and multi-response optimisation. It explains and presents the results using tables and charts. Chapter 6, the final chapter of the thesis consists of conclusions. First and second sections of this chapter describe research summary and the contributions to knowledge and practice. Third and fourth sections present research limitations and further research directions.

CHAPTER 2 LITERATURE REVIEW

The first objective of this research of identifying the main factors which affect the environment during turning operation was achieved through the detailed literature review. Initially, the key factors of environmental impact were identified. Then the literature review was further extended to identify the different strategies to reduce identified factors.

2.1 Sustainable Manufacturing

The interconnection between at all levels of economy, society, and environment is the core of the concept of triple bottom line sustainability. According to the definition given by the Department of Commerce in the USA, sustainable manufacturing is “the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [1]. In other words, it can be said that sustainable manufacturing refers to the efficient use of non-renewable resources and identifying substitutes for them by using renewable or natural resources [9]. This could yield not only environmental benefits but also financial benefits to any organization. Therefore, with the increasing scrutiny and consumer preferences, modern industries are now turning towards reducing the adverse effects on the environment without violating the environmental rules and regulations [9], [21].

In the present day, most of the industries are focusing on sustainable development and it results in more benefits to both industries as well as consumers. It is difficult to obtain a manufacturing process which has greater productivity and a less level of emissions [4]. Obtaining high-quality products following current engineering methods with less production cost and environmental impacts was identified as a challenge faced by modern industries [15], [22]. Even sustainable machining is defined well, most of the industries are failed to implement it [9]. To achieve sustainable production or machining process, the product’s life cycle which starts in the designing stage and ends at the stage of disposal should follow all the sustainable principles; minimize the usage of energy and material, diminish the impact on environment and waste, enhance the safety and health of persons and reduce the overall production cost [11].

To improve the sustainability of machining practices, it is necessary to take a holistic perspective of their impacts. Life Cycle Sustainability Assessment (LCSA) is a successful technique that can be used to improve sustainability in machining operations. The LCSA process can evaluate the possible impacts of different operations or products on the environment, society and economy holistically over their life cycles [23]. However, it is important to identify the sources of impacts in the aforementioned areas before commencing the LCSA of a machining operation. The purpose of this literature review is to identify the main sources of environmental impacts during commercial turning operation and strategies, to reduce them.

2.2 Environmental impacts of turning operation

Environmental impacts can be caused by several resources including energy, material, solid, air and water [7]. To get a clear view of the main sources of environmental impact, 80 selected publications were analysed and the summary of the analysed literature is shown in Figure 2-1. According to that, the highest percentage of papers (37%) have mentioned that MWF is the key contributor to environmental pollution. At the same time, 34% of papers have stated that energy consumption during machining is the main source of environmental impact. The percentages of papers that have been identified the emissions, waste materials, and water as the key factors contributing to environmental impacts are 13%, 9%, and 5% respectively. The least amount of papers (2%) have stated that the impact of metallic dust generated during machining on the environment is significant. Therefore, it is clear that the utilization of energy and MWF result in different negative effects on nature. Thus, is critical to reduce both aspects when improving the sustainability of machining.

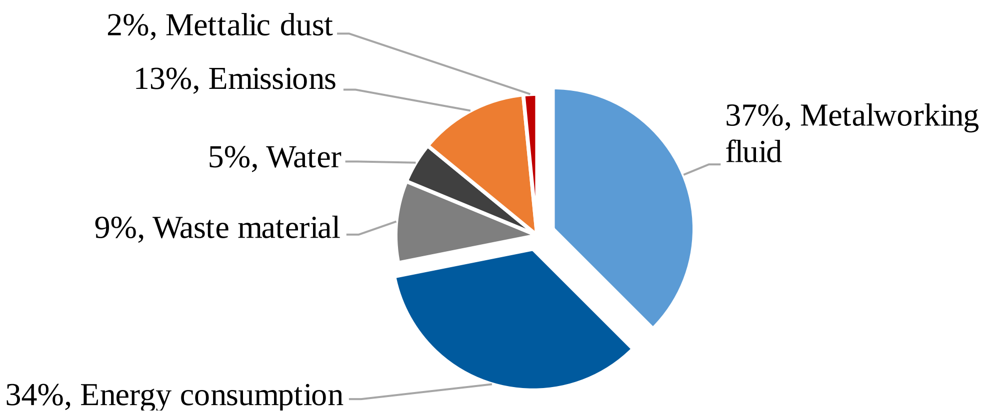

Figure 2-1: Share of literature entries on the factors of the environmental impact of conventional machining

2.2.1 Impacts of energy consumption

Energy use in any application results in a variety of impacts due to emissions, resource use, and other effects on ecosystems. A study related to the environmental impact due to the turning and milling tools has stated that almost 99% of impacts are created as a result of energy use [24]. Higher usage of energy increases the Carbon Dioxide (CO_2), Sulphur dioxide (SO_2) and Nitrogen oxides (NO_x) compositions in atmospheric air, which are referred to as key greenhouse gases [13], [25]. The reason behind this is the generation of electricity using fossil fuel resources, which is considered as the biggest source of CO_2 gas [26], [27]. Moreover, the production of bioenergy using biomass also emits CO_2 to the atmosphere [28]. In the early 21st century, CO_2 has contributed to around 65% to global greenhouse gases. From that, approximately 24% of CO_2 was emitted due to power generation [29]. Increasing concentration of the above gases in the atmosphere leads to global warming and other significant environmental changes [30].

Dambhare et al. [4] have mentioned machining as the highest energy utilizing and waste-producing industry. Many studies have been conducted to identify the factors that contribute to this high energy consumption. Energy requirement for machining processes can be classified into five categories; energy need for cutting tool production process, workpiece material preparation, tool changing process, various machine operations, and cutting process [31]. The cutting process can be achieved using different types of tools. Selecting of a cutting tool depends on the machining process, workpiece material and the cutting parameters. Nowadays, carbide tools or tool inserts are widely used. The production process of such carbide inserts requires special materials. Tungsten is one of the most commonly used materials, which is normally considered as an energy-intense material, having around 400MJ/kg of embodied energy. Sintering and physical vapour deposition (PVD) or chemical vapour deposition (CVD) are key steps in cutting tool manufacturing process. The process of cutting tool forming is named as sintering while the coating of tool happens in the stage of CVD or PVD. Cutting tool coating also requires more energy, and the estimated value of it is lying in between 1 MJ and 2 MJ per one cutting tool in a single process. Workpiece manufacturing processes consume a noticeable amount of energy as well as the resources relative to the entire machining process. Steel and Aluminium are materials that hold the high ranks in the above respect. To produce steel from unspoiled resources it needs around 31MJ/kg. However, when it is produced from the used materials it needs only 9MJ/kg. The production process of Aluminium needs nearly 219MJ/kg [13]. Even if the energy required to produce tool and workpiece materials does not directly contribute to machining energy use, it contributes to the overall embodied energy use and impacts of machining [29].

The tool changing process also requires a considerable amount of energy. It depends on the duty cycle of the machine and may vary during machining. It can be achieved through automated equipment, motors and drives of cutting tools. Around 30% of the total energy usage of machining is spent on changing tools [32]. Besides the actual cutting operation, there exists many non-cutting operations, thus accounting for the highest portion of energy compared with other functions [24]. Chillers or water cooling systems, pumps and spark generators are known as the greatest energy-intensive units required for non-cutting operations [33]. The power requirement for starting the motors, fans, lights and computers in the shop floor and quick motion of axes jog to its home position can also be considered in this category [34]. Cutting energy is the next important factor, and it depends on the workpiece material properties, metalworking fluid quality, quality of the tool, and cutting parameters [35]. Normally, cutting energy represents the energy required for the cutting tool to obtain a required quality of the machined surface [11]. However, in reality, the energy supply to the cutting tool is not totally utilized for the material removing process, as some fraction of it converted to the heat and noise [36]. The specific cutting energy for Aluminium alloys varies between 0.4 J/m3 and 1.1 J/m3, while for steels it varies between 2.7 J/m3 and 9.3 J/m3. The actual cutting energy is truly small compared with other energy components, being less than or equal to 15% [13], [34], [35].

Reduction of energy consumption can be achieved in two ways; reducing the steady energy of machine tools and auxiliary components and reducing the fluctuating energy usage during machining which is governed by the cutting parameters [11]. Several studies have focused on quantifying the effects of different cooling techniques and modified cutting tools on fixed energy use and optimisation of cutting parameters on variable energy use. A detailed review of the aforementioned strategies is presented in section 2.3.1.

2.2.2 Impact of metalworking fluid consumption

Metalworking fluid (MWF) is considered to be the next major source of impacts, not only on the environment but also on human health. It has been identified that MWF is one of the most critical health threats for the workers [11], [37]. Most of the MWFs used in industrial operations are made from mineral oils that are extracted from the crude oil [9], [21]. Therefore, they are non-biodegradable and toxic in nature [38]. Based on the average values for MWF extraction, around 160 L of crude oil is required to extract 2 L of MWF. Most of the byproducts from this extraction process are emitted to the environment [9]. Ecological problems associated with MWFs are spread across the globe [13]. At high machining temperatures, the MWF chemically breaks-down, resulting in inhalation and dermal contact of MWF with the human body and contamination of soil and water when MWF is disposed of [8], [17]. The spattering of MWF leads to diseases in the machine operators’ lungs, stomach, prostate etc. in addition to the economic costs of wasted MWF [39]. Furthermore, some of the additives in MWFs cause depletion of the ozone layer [13]. The microorganisms such as fungi, bacteria and algae can grow within media such as water-soluble cutting fluids. It results in diminishing the cooling capability of those fluids and change its pH value. Corrosion of machine inserts or tools and the workpiece are caused by improper pH values of MWF [21]. Special anti-bacterial additives can be used to control the process of bacteria growth. However, the use of those chemicals again in turn contribute to the environmental impact as well as the operators' health [40].

Continues usage of MWF leads to deposition of additives formed from Chlorine and Sulphur in the workplace. With time, these deposited additives start to vaporize. Then they can be absorbed by the human body via inhalation. Ultimately, it causes a significant health hazard and also the vaporized additives could leave the shop floor with bad odour [41]. According to data from the National Institute of Occupational Safety and Health (NIOSH) in the USA, more than one million of machine operators are victims of various skin and respiratory problems due to MWFs [21]. Sujan et al. [42] have stated that approximately 80% of operators' infections are caused by dermal contact with MWFs during their work. Disposing of used MWFs too creates a massive environmental footprint. In the USA, the amount of used MWF disposed to the environment per year is more than 150 million gallons [40]. Besides the direct environmental footprint of MWF, there are indirect environmental impacts. MWF circulating system increases the electricity consumption during machining because of the auxiliary components, ultimately leading to higher environment impacts [6]. Even though MWFs are thus known to cause many environmental and health issues, various MWFs are used in the industry as standard practice [10], [22].

The level of environmental impact due to the MWF depends on the cooling technique because different cooling techniques consume different amounts of MWF. Flood cooling uses a comparatively larger amount of MWF, and it is widely used in the industry [10]. Several experiments have been conducted on using alternatives for flood cooling. Even though those alternatives have can result in a reduction of MWF consumption, they have other disadvantages as described in section 2.3.2.

2.3 Mitigating the environmental impacts of turning operations

This section describes the several strategies that can be used to reduce the most critical environmental impact during turning operation, arising from energy and MWF consumption. Reduction of energy and MWF use can be done by various means, as described below.

2.3.1 Reduction of energy consumption

Optimizing energy efficiency in machines and machining is very important. Because it leads to lower the consumption of energy, cost for energy, adverse effects on the environment and ultimately enhance sustainability in machining. Therefore most of the industries and research articles are paid their attention to the development of efficient manufacturing operations. The energy efficiency of the cutting operation has been defined according to Equation 2-1 and it varies in between 1% and 6% [35].

$$Energy\ efficiency = \frac{Net\ cutting\ specific\ energy}{Machine\ specific\ energy} \qquad \text{Equation 2-1}$$

To survive under decreasing energy resources with increasing population, it is necessary to achieve greater efficiencies in energy utilization. But the industries don't have enough economic background to purchase new machines with high technology and efficiencies. Therefore the best method to achieve energy efficiency is the improvements in machining operation using existing machines [29]. Optimisation of energy consumption can be achieved through the use of most convenient cooling technique, modified cutting tools and machining parameters.

2.3.1.1 Using different cooling techniques

Lubrication during machining is necessary to ensure better output quality. However, the energy demand for such lubrication mechanisms hinders sustainability motives. There are many experiments conducted to identify the effect of energy consumption during machining due to usage of different cooling techniques. Cooling during machining can be achieved in different ways; flood, MQL, cryogenic, HPJAM, and solid lubrication. The energy requirement depends on the cooling technique due to use of different auxiliary components and modes of turning (rough, medium or finish).

The flood lubrication is a conventional cooling technique widely used in the industry. However, the cost associated with the flood lubrication and the environmental impact due to the usage of MWF is higher with this technique. Therefore, as previously mentioned, it is necessary to find alternatives for flood lubrication [10]. Campatelli [17] has identified two main sources of environmental impact with flood lubrication; energy consumption for the MWF pump and disposal of solid waste (chips). The MWF pump in flood lubrication system needs constant energy when the machine is powered

ON. Then, additional energy is required to circulate the MWF during flooding/lubricating (which is variable) [32]. Gutowski et al. [43] have estimated the pattern of energy consumption during both idle stage and actual machining stage. According to that the above study, more than 30% of the constant energy consumption is for the MWF pump.

The minimum quantity lubrication (MQL) is one alternative for flood cooling, which supplies the MWF as a mist to the cutting region [44]. To generate the MWF mist, it is required to convert the liquid of MWF into droplets with a diameter range from 15 µm to 40 µm [45]. The MWF mist generation process is achieved through the mixing of liquid of MWF and compressed air [46]. In previous literature, the compressed air for MQL systems has a pressure range between 2 bar to 23 bar [47], [48]. Most of the time, compressed air for the MQL system has been taken from an external air compressor [49]. The air compressor is the key source of the environmental impacts of the MQL system. Campatelli [17] has experimentally proved that the amount of CO2 emitted to the atmosphere due to power consumption of air compressor in MQL system is higher than that of the flood lubrication system. Numerically, the equivalent CO2 emissions due to the turning of 1kg of AISI 1040 under flood lubrication is 70 g, while under MQL it is around 75 g, as demonstrated by Figure 2-2.

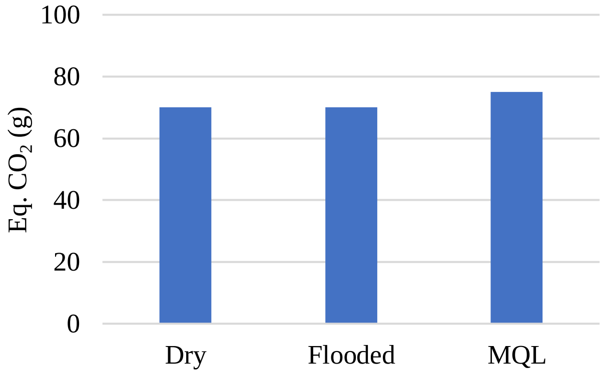

Figure 2-2: Amount of CO_2 due to different cooling conditions used in [17]

The cryogenic lubrication is also considered to be a better alternative for flood lubrication technique. This allows conducting machining operations to be conducted at temperatures less than 120 K [40]. Liquid nitrogen (LN_2) is the mostly used MWF for cryogenic lubrication [46]. The process of LN_2 generation uses atmospheric air as the raw material input, while water and energy are used for secondary processes such as compressing and cooling. LN_2 is acquired as the usable output of this process, while the rest of the byproducts are released to the environment as waste [9]. Separation of air consists of six main steps; air compression, air purification, heat exchanging, distillation, refrigeration, and vaporization [50]. Some authors have stated that the energy consumption during machining under cryogenic lubrication condition is comparatively less than that during flood lubrication and it is also a more economic cooling technique [51], [52]. However, the energy requirement for the LN_2 production process per year is around 13.5×10^4 MJ while that for the conventional MWF (mostly use in flood lubrication) is around 820 MJ [9]. Hence, the environmental impact due to energy usage during LN_2 production is higher.

High pressure jet assisted machining (HPJAM) is another alternative for flood lubrication. It is a cooling technique that applies a jet of MWF or water at a high-speed to the cutting region [53]. This machining method has been used for the machining of difficult-to-cut materials; nickel-based alloys [54], titanium alloys [55] and ferrous alloys [56]. Pusavec et al. [32] have examined the energy consumption during turning operation of Inconel 718 using SANDVIKGC 1105 grade carbide tool inserts under HPJAM condition, cryogenic lubrication and flood lubrication. Table 2-1 gives a summary of the results of the study [32]. There is a significant increase in energy consumption during machining under HPJAM condition due to the use of an additional pump at high-pressure compared to the other two machining modes.

Table 2-1: Results of energy study during turning of Inconel 718 (Source: [32])

Cutting parameters	**Cooling technique with technical specification**				**Energy consumption (kWh) per workpiece at different cutting speeds, V_c (m/min)**		
	Technique	**Specifications**					
		MWF	**Pressure**	**Flow rate**	**30**	**60**	**90**
f = 0.25 mm/rev a_p = 1.2 mm	Cryogenic	LN_2	1 MPa	0.6 kg/min	0.147	0.077	0.055
	Flood	Vegetable oil-based	-	6 l/min	0.148	0.082	0.076
	HPJAM		50 MPa	1.5 l/min	0.202	0.105	0.073

Solid lubrication has been used in literature instead of flood lubrication to avoid the use of MWF during machining [57]. In this technique, solid particles show as lubricants. Two solid lubricants, molybdenum disulphide (MoS_2) and graphite have been used largely in the past [46]. Rao et al. [58] have explored the effect of particle size of the solid lubricants on machining parameters during turning of EN 8 steel. In the above study, both graphite and boric acid (H_3BO_3) with different particle sizes have been used as solid lubricants. The results of this study show that solid lubrication can result in better surface roughness as well as lower tool flank wear and tool temperature compared to dry machining and flood lubrication. However, to obtain the 2 - 3 g/min mass flow rate of solid lubricants, an air compressor with a pressure range of 0 - 0.3 MPa is used. The additional energy consumption due to existing air compressor has not been examined in detail. In another study, it has been mentioned that extra energy is needed to produce suitable cutting tools or inserts for this technique [38].

Dry machining is a technique where machining is done without MWFs. Use of dry machining increasing as it leads to an overall reduction of costs and environmental impacts in machining, due to the absence of MWF [59]. Diniz et al. [60] have mentioned that dry machining fails to dismiss the heat produced at cutting region and therefore, increases the friction between the workpiece and the tool-tip. Due to this, the cutting tool undergoes a higher thermal load and ultimately the tool life is reduced. However, another study shows that dry machining results in better machining performance in terms of tool life compared with flood lubrication during turning of duplex stainless steel [61]. From a sustainability perspective, dry machining needs less energy due to the absence of auxiliary components such as pumps and filters. Available literature based on energy consumption during turning under different cooling conditions is summarised in Table 2-2.

Table 2-2: Patterns of energy consumption during turning under different cooling techniques

Material	**Cutting parameters**	**Cooling technique**	**Energy consumption**		**Ref.**
			Unit	**Compared result**	
AISI 1045 steel	a_p = 1 mm f = 0.1, 0.14 mm/rev V_c = 430, 540 m/min r_ε = 0.4, 0.8 mm	Dry Flood	Current (A)	Low High	[60]
AISI 1040 steel	a_p = 1 – 2 mm f = 0.04 – 0.16 mm/rev V_c = 200 m/min ± 5%	Dry Flood MQL	Specific energy (kJ/kg)	0.43 0.39 0.37	[17]
AISI P-20 steel	a_p = 0.20, 0.35, 0.50 mm f = 0.10, 0.12, 0.14 mm/rev V_c = 120, 160, 200 m/min r_ε = 0.4, 0.5, 1.2 mm	Dry Flood Cryogenic	Power (W)	Medium High Low	[52]
Ti6Al4V	a_p = 0.8 mm f = 0.1, 0.2 mm/rev V_c = 90, 120 m/min	Dry MQL Cooled air Flood Cryogenic	Cutting energy (kWh)	Depends on the cutting parameters	[41]
Duplex stainless steel	a_p = 2 mm f = 0.3 mm/rev V_c = 100 m/min	Dry Flood	Specific cutting energy (J/mm3)	Low High	[61]
Ti-6Al-4V	a_p = 2.0, 0.5 mm f = 0.30, 0.10 mm/rev V_c = 65 m/min	Dry Flood	Specific cutting energy (kJ/cm3)	44.3 228	[62] [63]

2.3.1.2 Modified cutting tools

The parameter cutting energy represents the energy needed for the cutting tool to obtain the required quality of the machined surface. Some authors have suggested that energy consumption can be minimized through the optimisation of tool life [11]. The movement of the cutting tool during both facing and straight turning operations using one cutting tool leads to greater nose wear. A new approach has been suggested by Fredrik et al. [37] to reduce the tool nose wear of the turning process. According to the above, the cutting tool insert is fed in both directions during the straight turning operation. By using this newly proposed method, the energy usage during turning can be reduced by nearly 12% compared to the traditional method.

Gaitonde et al. [64] have conducted a study to identify the fluctuation of power consumption during turning of AISI D2 steel concerning the tool type. For this study, three TiN coated ceramic inserts (CC650WG, CC650, and GC6050WH) have used. The experiments have been conducted under two varying parameters; axial depth of cut (a_p =0.2, 0.4, 0.6 mm) and time (t= 5, 10, 15 min), while keeping spindle speed and feed rate as constant values at 80 m/min and 0.10 mm/rev respectively. The power consumption during each experiment has been calculated by measuring the cutting force. The results of this study show that the cutting insert, CC650 has a lower power consumption under all levels of variable parameters compared to the other cutting inserts.

Another study has been performed considering turning of Ti-6Al-4V to examine the combined effect of cryogenic technique and modified cutting inserts on tool wear. In this study, TiAlN coated cutting inserts were modified to enhance the cooling effect by preparing holes on both rake and flank faces of cutting. The tool flank wear under both flood lubrication (with standard cutting insert) and cryogenic lubrication (with modified cutting insert) was examined with variable cutting velocities. The tool flank wear has reduced by approximately 39% with the cryogenic condition compared to the flood lubrication [65].

One study has been conducted using a self-lubricated cutting tool during turning under dry conditions. In this study, micro-holes were prepared on the faces of rake or flank of the cutting tool. The solid lubricant MoS_2 was filled into these micro holes to make self-lubricated cutting tools. It was observed that a significant reduction of cutting forces and flank wear can be obtained by this compared to a conventional cutting tool [66].

Experiments using rotary cutting tools for turning operations have been reported since 1865 [67], and Armarego et al. [68] have conducted a comprehensive study about this kind of tools. An experiment has been conducted using a rotary cutting tool. The results of this experiment have been shown that, at the best cutting condition, rotary tool’s life time can enhance up to 64 times of nominal tool life of a conventional cutting tool [69]. None of the above experiments has evaluated the effect of newly developed cutting tools on energy consumption. As mentioned by Hanafi et al. [11], it can be assumed that the energy usage during turning operation using a self-lubricated cutting tool and a rotary tool will be less than the conventional cutting tool. The cost associated with producing these kinds of new tools will however be significant. Furthermore, the environmental impact due to the use of solid lubricants was not highlighted. Therefore, even if new cutting tools are introduced, their influence on the overall sustainability is yet to be verified.

2.3.1.3 Optimised machining parameters

The spindle speed, depth of cut and feed rate are the three key parameters that are required to obtain a better machining performance and lower the energy consumption [70]. Carmita [24] and Bhushan [71] have stated that cutting energy can be reduced by increasing cutting speed, and feed velocity. When the cutting speed is higher, a larger quantity of material is removed in lesser cutting time. The spindle is accelerated to increase the spindle speed from zero to the ultimately required value, and that process of acceleration consumes energy. However, this is not considered as cutting energy. When the feed rate is increased, the feed axis moves fast and the cycle time is reduced [6]. Moreover, it leads to a decrease in the cutting force per unit cross-sectional area [60]. Therefore, the energy requirement decreases. The depth of cut is the next important machining parameter. According to the literature, lowering the depth of cut results in reduced energy consumption during turning. If the depth of cut is raised, it requires a higher force to remove workpiece material, thus increasing the cutting energy [6].

It is difficult to conclude about the most influencing cutting parameter on energy consumption during turning operation, as it depends on other cutting conditions such as workpiece material, cutting tool, cutting tool’s geometry, and cooling technique. Table 2-3 gives a summary of the most influential parameters on energy consumption during turning of different materials under variable cutting conditions.

Table 2-3: The most influencing parameters on energy consumption during turning of different materials

Material	Cutting tool	Cooling technique	Influencing parameter	Analysing Method	Ref.
AISI 6061 T6	Carbide insert	Flood	f	Taguchi ANOVA	[24]
7075 Al alloy	Carbide insert	-	V_c	RSM ANOVA	[71]
PEEK-CF30	TiN coated cutting tools	Dry	a_p	RSM ANOVA	[11]
AISI P20 tool steel	TiN coated cutting tools	Dry Flood Cryogenic	V_c	Taguchi ANOVA	[52]
AISI 1040 (EN-8)	Brazed ceramic tool TiN coated cutting tool TiAlN Coated cutting tool	Dry Flood MQL	V_c	RSM ANOVA	[4]
AISI 1045 steel	Carbide insert	Dry	V_c	Taguchi ANOVA	[72]
AISI 1045 steel	Uncoated tungsten carbide tools	Dry	f	Taguchi ANOVA	[73]
AISI D3 steel	TiN coated cutting tools	Dry	a_p	Taguchi ANOVA	[74]
AISI 420 steel	TiN coated cutting tools	Dry	a_p	Taguchi ANOVA	[75]
AISI 1040 Steel	Carbide insert	Flood	V_c	Taguchi ANOVA	[76]

2.3.2 Reduction of metalworking fluid consumption

As described in section 2.2.2, MWF consumption during turning operation leads to different direct and indirect impacts on the environment. To reduce the effects on the environment by reducing the quantity of MWF applied to the cutting region following strategies can be used.

2.3.2.1 Using different cooling techniques

The MWF is required to cut down the temperature at the tool-tip, the friction within chips and tool, the heat generation at the cutting region, and the cutting forces. However, the use of MWF leads to environmental and human health problems as mentioned earlier [60]. The consumption of coolants for machining purposes in 2006 was approximately 52% of the total coolant use [77]. The cost associated with MWF largely affects the overall machining cost. Its cost of treatment and disposal after machining is nearly 1.5 times its purchasing cost [78]. Hence, the reduction of MWF consumption leads to a corresponding reduction in the issues related to the environment, society, and economy. Wet machining uses a large quantity of MWF during turning operation. Cryogenic machining, HPJAM, dry machining, MQL, and solid lubrication have been identified as alternatives to flood lubrication technique [10].

In cryogenic lubrication, the used liquefied MWF is evaporated to the atmosphere and the production of harmful residue during machining is zero [22]. However, as previously stated, the energy required for the production of LN_2 is higher. Hence, the cost of this system and environmental impacts are also high [21]. The HPJAM allows using a low amount of MWF at high pressure. It can provide efficient cooling action near the cutting region. However, the energy requirement for HPJAM system leads to an increase in the total cutting energy and hence the environmental impacts [9]. The dry machining has been identified as a better technique to reduce the cost of machining and environmental issues. The main problems associated with this technique are metallic dust formation and deficient machining performances [79]. The MQL uses on a minute amount of MWF, generally at a flow rate within 50 and 500 ml/hour [80]. However, the formation of mist leads to an increase in the toxic compounds in atmospheric air, ultimately creating adverse effects on the occupation’s health. The environmental impact which is caused by the solid lubrication technique is minimum due to the absence of MWF. However, it requires additional energy and costs to make the cutting tools suitable for the technique of solid lubrication [21]. Therefore, even though the aforementioned cooling techniques diminish the usage of MWF, they lead to different indirect issues related to the environment and economics of machining. The identified advantages and disadvantages of alternatives of flood cooling are summarised in Table 2-4.

Table 2-4: Advantages and disadvantages with implications on the sustainability of alternatives to flood cooling

Cooling/ lubrication technique	**Advantages**	**Disadvantages**
MQL	▪ Lower the consumption of MWF	▪ Creation of mist causing health hazards ▪ Required additional components and energy ▪ High cost
Cryogenic machining	▪ Chips can be recycled as scrap metal ▪ Leaves no harmful residue to the environment	▪ If the temperature difference is high, the accuracy of the machining operation is deficient ▪ Higher initial costs ▪ Energy-intensive production process
Dry Machining	▪ Less machining cost ▪ The easy chip recycling process and low cost ▪ Less energy consumption ▪ Zero consumption of MWF	▪ A higher amount of heat is generated in the cutting region ▪ Poor machining performance for some materials ▪ Formation of metallic dust
Solid Lubrication	▪ Zero consumption of MWF	▪ Additional cost and energy are required to produce special cutting inserts for this technique
HPJAM	▪ Lower the consumption of MWF	▪ Required additional components and energy

2.3.3 Identifying the best strategy for impact mitigation

Even if the aforementioned several strategies have been applied to improve the turning operation, it is necessary to consider multiple parameters from a sustainability perspective. Moreover, it is difficult to calculate the overall environmental impacts of turning just by observing the machining operations and the energy consumption of directly used equipment, as there are some hidden sources of environmental impacts. As an example, the cutting tools and workpieces contain a significant amount of embodied energy due to their production process. Hence, a standard method should be used to determine and quantify the environmental impacts of turning operations. For holistic sustainability in manufacturing, the three pillars of environment, economy, and society should be considered simultaneously [10]. This concept is known as the “Triple Bottom Line” sustainability [23]. The Life Cycle Sustainability Assessment (LCSA) is a standard process that can be used for this type of sustainability assessment. Section 2.4 describes the development, applications, and limitations of LCSA.

2.4 Life Cycle Assessment

The development of Life Cycle Assessment (LCA) was performed by industry and universities together in 1960 [81]. In 1969, the first LCA of a product was conducted. Earlier, this technique was named as “Environmental Profile Analysis”, and it was used to recognize the environmental impacts of several beverage packaging materials and sanitary products for infants [82], [83]. Since then, LCA has been used in various fields such as construction [84], agriculture [85], transportation [86], food processing [87] and manufacturing systems [88].

A survey based on the practices of LCA in large corporations was conducted in 1995. For this survey, companies under the three categories Hi-Tech, Intermediate, and Personal care were considered. The results of this survey show that more than 50% of companies had used LCA to analyse the environmental impacts, to reduce marketing and cost-related problems. Moreover, six main stages have been identified where LCA can be applied; extraction of coarse material from the earth, manufacturing, transportation, product use, recycling, and disposal. However, the more companies are trying to reduce environmental issues in manufacturing stage compared to other stages, as the manufacturing process is totally controlled by the organization [89]. Another survey has been performed by Cooper et al. [90] in 2005 to identify the application of LCA results for different purposes. The results of this survey show that LCA results are largely used in business strategy as well as process and product research and development. The use of LCA in the fields of education, policy development, sales, and procurement is also significant.

Due to the increasing usage and interest in LCA, standardizing was required. As a result of that, legal standardization of LCA was started in 1993 under the authority of the International Organization of Standardization (ISO) [81]. Finally, series of standards for LCA has been introduced, addressing different stages; ISO 14040 (Principles and framework) [91], ISO 14041 (Goal and scope definition and inventory analysis), ISO 14042 (Life cycle impact assessment) and ISO 14043 (Life cycle interpretation). Furthermore, the abovementioned four standards have been revised in ISO 14044 [92].

Life Cycle Sustainability Assessment (LCSA) is a combination of impact assessments in three areas pertaining to environment, economy, and society. Life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA) are the three components of LCSA [23]. The standardized tool of LCA allows analysing the environmental and potential impacts of a product or a process. The theory of LCC is used to evaluate the life cycle cost of a product [93]. It has been used before the application of LCA and there are some similarities between LCA and LCC [23]. LCSA has further developed and evolved with industrial needs [94]. A method named Product Sustainability Assessment (PROSA) has been suggested for sustainability appraisal of products produced by small and medium companies. Four different models have been developed for the evaluations. The main model, ProFitS is for the overall sustainability assessment of the product. The other three models, EcoGrade, SocioGrade, and BeneGrade are used for assessing the impacts on the environment, society, and utility respectively [95].

There are variants of LCA, decided based on the stages considered for the assessment. Cradle-to-grave, is a full LCA that studies all impacts related to the resources, ecological systems and human health of a product throughout its life cycle from raw material extraction through use phase to the disposal stage [96]. Cradle-to-gate is the LCA of a product from raw material extraction through the manufacturing process to the factory gate. In the cradle-to-cradle variant, the life cycles of recycling products are included in the cradle-to-cradle assessment [97]. Gate-to-gate, also a partial LCA directs on one or a few of the value-addition processes of a product's whole manufacturing chain. A full cradle-to-gate LCA of a product can be obtained by linking gate-to-gate LCAs of different processes of the product [98].

The LCA of a product or a process consists of four steps;

I. Defining the goal and scope – Initializing the objectives of the study and identifying the system boundaries. Here, the stage of product or process life cycle that is going to be assessed and the output should be clearly defined. The scope of the study should consist of the product system, functional unit, system boundaries, selection of impact assessment methodology, assumptions, and limitations [91]. The system boundary depends on the variant of LCA.

II. Inventory analysis – Identifying the inputs and outputs in terms of energy and material of the product or process system. Then, the interaction of those things with the environment in terms of emissions and usage of resources are considered.

III. Life cycle impact assessment – In this stage, the results of impacts in terms of different indicators are converted into a single impact unit. Furthermore, their importance is assessed. The methodology of impact assessment can be selected considering the study goal and scope [91].

IV. Interpretation of results – Interpretation of the impact assessment results and inventory analysis is done to achieve the goal of study. It involves sensitivity analysis and representation of results based on the particular application [28], [97].

2.4.1 Evidence of Life cycle assessment-based research

A study was conducted to identify the most suitable reference flow to investigate the influence of varying cutting parameters on the environmental footprint of cylindrical plunge grinding of 21-2N steel using LCA technique. In this study, the LCA software, GaBi (Professional version 6) was employed to investigate the environmental footprint in terms of acidification potential (AP), global warming potential (GWP), freshwater aquatic toxicity potential (FAEP), abiotic depletion potential (ADP) and human toxicity potential (HTP) using CML 2001 method. It was identified the environmental impact using two reference flows; one second grinding operation and machining of the single workpiece. Finally, it was concluded that machining of the single workpiece is the best reference flow for deep evaluation of the influence of varying cutting parameters on the environmental impact [99].

Another study was conducted to identify the level sustainability of cooling techniques; high-pressure jet assisted machining (HPJAM) and cryogenic machining, following the LCA tool. This is a case study based research. The authors concluded that usage of cryogenic machining leads to a considerable reduction of global warming potential, usage of water, solid waste and acidification compared to the flood lubrication. However, the adverse result of cryogenic lubrication is an increasing amount of energy use for MWF production. The authors suggested that switching from mineral oil-based MWF to natural oil-based MWF can follow as the very first step of achieving sustainable machining operation [9].

Andres et al. [100] developed an LCA model to investigate the environmental impact associated with four different MWF systems; petroleum oil in water, petroleum oil in air, rapeseed oil in CO_2 and, rapeseed oil in water. It was selected one year as the functional unit. For the LCA, energy consumption and MWF consumption were considered as environmental input. The environmental outputs, emission factors were gathered from SimaPro software or from the literature. But the emissions during the transportation of MWF weren't considered. The environmental impacts due to the use of MWF were identified under seven impact categories; water usage, aquatic toxicity, solid waste, non-renewable energy use, land occupation, acidification potential and, global warming potential. Graphical representation of the identified impacts in this study is shown in Figure 2-3. According to that, the authors concluded that use of air-based MWFs leads to a 90% reduction of water use, 60% reduction of solid waste and 80% reduction of aquatic toxicity. However, the use of air-based MWF systems for some machining operations is limited due to lack of lubrication and cooling capabilities. It was suggested the superficial CO_2 media as a better solution for that particular machining operations. The effect of global warming potential from air-based MWF systems is high contrast to the oil-based MWF systems. The reason behind that is, releasing global warming emissions to the atmosphere from air-based MWF systems than the oil-based MWF systems. Finally, the authors concluded that air-based MWF causes a smaller environmental footprint compared to the oil-based MWF.

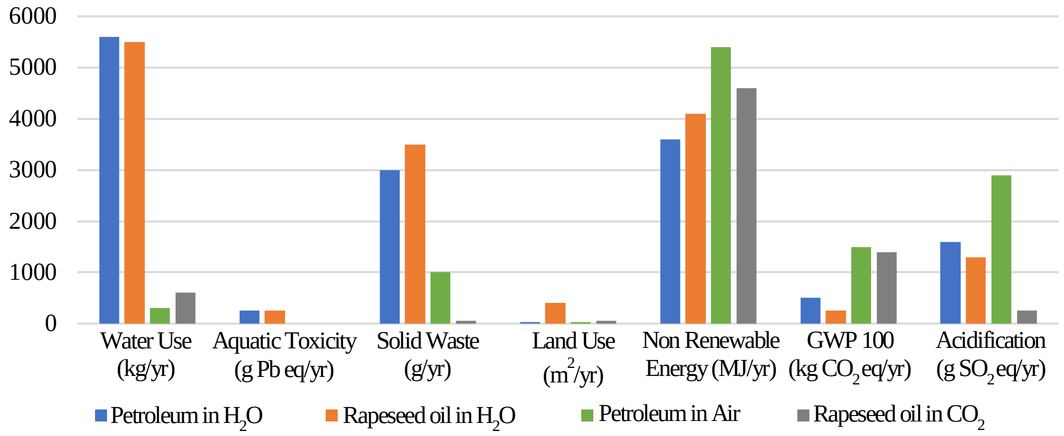

Figure 2-3: Environmental impacts of different MWF systems in the use phase (Source: [100])

A study was performed to identify the effect on the environment in turning operation of Ti-6Al-4V under three levels of feed rate, cutting speed and machining conditions; dry, cryogenic with simple nozzle and cryogenic with two nozzles. During all experiments, the depth of cut was maintained as a constant value of 1.0 mm. In this study, multi-objective optimisation of specific energy, temperature, cutting force and surface roughness were focused. For the LCA one machined workpiece was considered as the functional unit. To analyse damage to human health and the environment, Simapro software with European database and impact assessment methods, Impact 2002+ and EPS 2000 were used. According to the results, the authors stated that both surface roughness and cutting force can be minimized using smaller feed rate (f) and larger cutting speed (V_c). The temperature at the cutting region would be minimum at lower values of "f" and "V_c" while their higher levels lead to minimizing the specific energy. Moreover, they concluded that specific energy can be slashed by raising the material removal rate (MRR).

As mentioned in the above paragraph, the impact assessment was conducted using two different methods. Furthermore, only the use phase of the cryogenic condition was considered for this part. The results of different impact categories, obtained using the impact assessment method, EPS 2000, is shown in Figure 2-4. According to that, the authors highlighted that the highest impact on both abiotic resource depletion and human health were produced by the dry machining (experiments number 1, 4, 10 and

19). The impacts on both ecosystem and biodiversity due to the use phase of dry and cryogenic machining can be neglected.

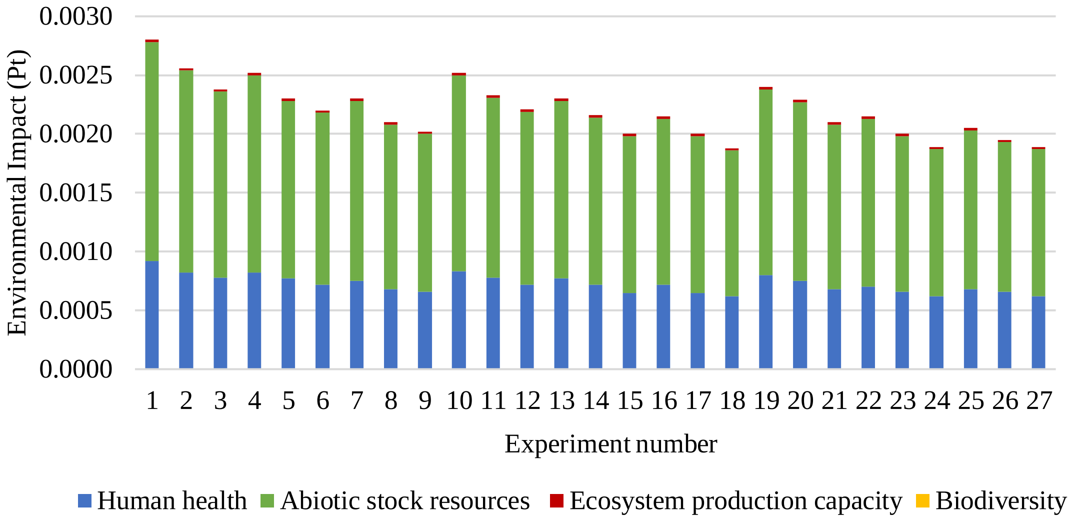

Figure 2-4: Analysed environmental impact of different cooling conditions using the method, EPS 2000 (Source: [101])

Furthermore, the analysed environmental impact using the assessment method, Impact 2002+ is shown in Figure 2-5. According to the results, it is clear that the same experiments were given the highest impact on human health, climate change and resources. But the impact on ecosystem quality is negligible compared with other impact categories. As stated above, the impact which was created by the dry machining is greater than that under cryogenic machining. The authors stated that the reasons behind that are the absence of disposal phase of MWF and high-speed flow of LN_2 helps to obtain a clean machining environment due to remove away the chips from cutting region. Moreover, it was mentioned that the lower specific energy under cryogenic condition may lead to the lower environmental impact [101].

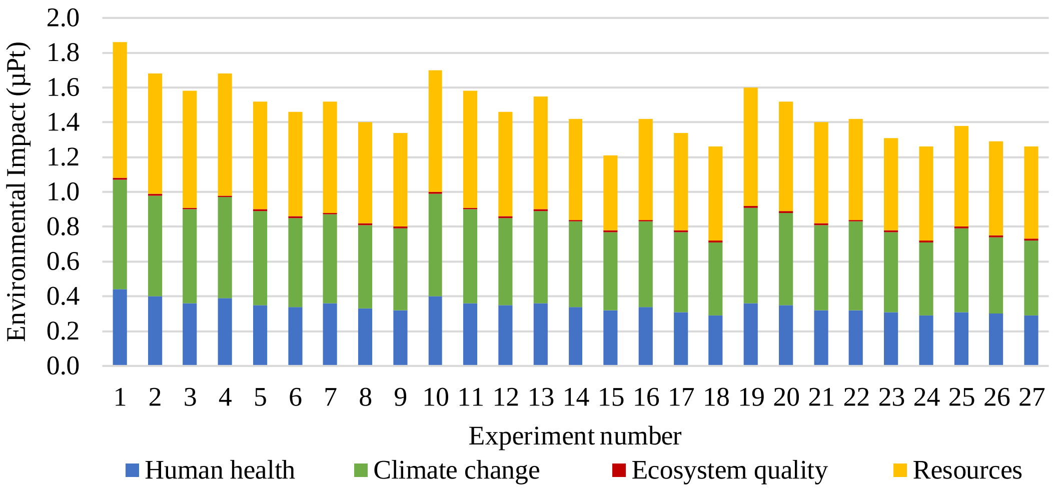

Figure 2-5: Analysed environmental impacts of different cooling conditions using the method Impact 2002+ (Source: [101])

Another study was carried out by Narita et al [102] to identify the environmental impact from the different components in milling operation. In this study, the impact category, global warming due to equivalent CO_2, N_2O and CH_4 were focused. To calculate the overall generation of CO_2 from the milling operation under MQL and dry machining conditions, the consumption of electricity and emissions were examined. The results of this study were shown that the contribution from MQL system to global warming is smaller compared with dry machining condition. Furthermore, the authors concluded that the contribution of CO_2 which is generated milling operation related activities, to the global warming potential is the highest compared the contribution of N_2O and CH_4.

Alessio et al. [5] used the LCA tool to examine the resource efficiency of two different lubrication techniques; flood cooling (FL) and minimum quantity lubrication (MQL), during drilling (PD) and milling operations (PM) of aluminium, steel and cast iron. A gate-to-gate LCA for both drilling and milling operations was performed. The volume of the drilled hole or milled area were taken as the functional unit. For the impact assessment, the method, CML 2001 with the ecoinvent database was used. The environmental impacts under fourteen impact categories were analysed. However, the impact on abiotic resources, climate change and land use due to electricity, compressed air, MWF related purposes and tools production were highlighted. The analysed results for abiotic resource depletion is shown in Figure 2-6. According to that, a larger percentage of abiotic resources depletion was resulted due to the use of electricity and compressed air. The percentages of those two portions together were accounted for 65-100 %. The authors mentioned that electricity is responsible for a larger amount of resource use due to the consumption of coal and lignite for electricity generation. The resource consumption for tools production for the milling was obtained a significant percentage between 5% and 15% while that for drilling is negligible. The consumption of resources for the MWF related purposes was accounted for a considerable percentage in machining under flood lubrication condition compared that in MQL condition.

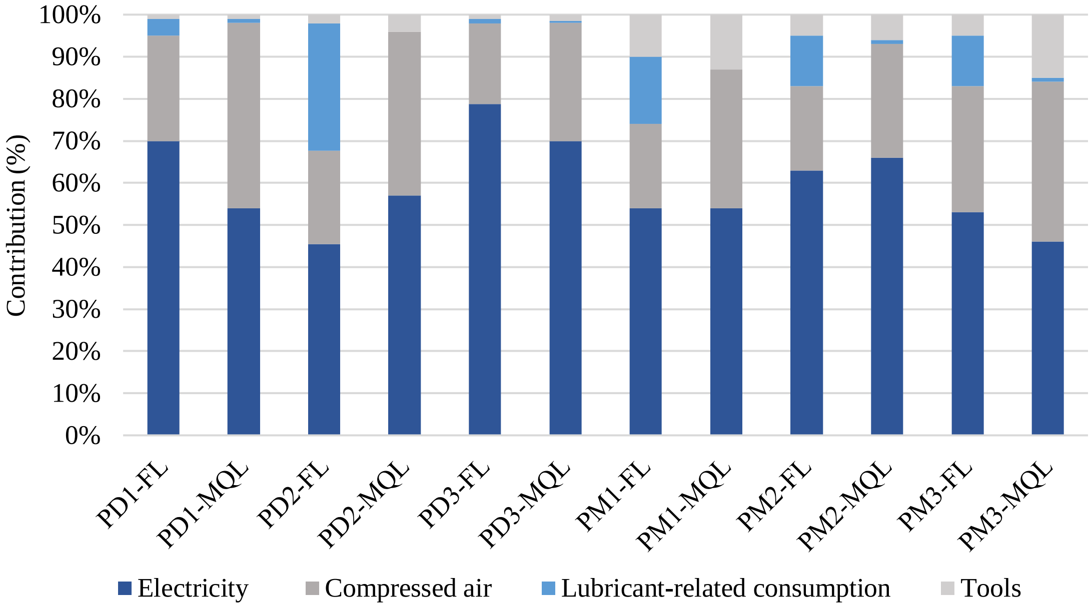

Figure 2-6: The analysed results for abiotic resource depletion (Source: [5])

The analysed results of climate change (CC) are shown in Figure 2-7. The results show that the contribution from electricity and compressed air to climate change was accounted for the highest percentages (together between 50% to 99%) in each machining condition. The authors concluded that CO_2, which is mostly generated from the burning of coal and lignite in the production process of electricity is the key contributor to CC. The effect of MWF related purposes on CC was obtained considerable percentages between 5% and 47% in all experiments which were conducted under flood lubrication condition. The authors selected the combustion as the final waste treatment of consumed MWF. Moreover, the production process of MWF has a high effect on CC. The impact which was created by the MQL condition is negligible. Due to the production of tools which were used milling operation, CC was influenced by approximately 5% - 15%, while that in drilling operation can be neglected.

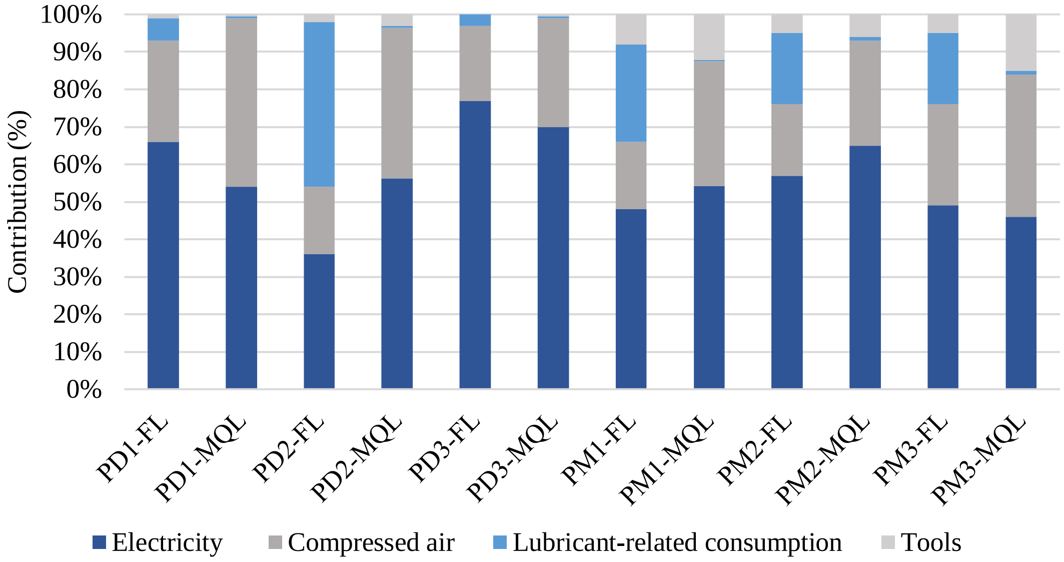

Figure 2-7: The analysed results for climate change (Source: [5])

Figure 2-8 represents the analysed results of land use (LO). It is difficult to identify the clear patterns of the effect of sources on LO. However, the authors were mentioned that LO is higher due to electricity generation and MWF related purposes. The impact on LO due to MWF related purposes in flood lubrication condition was contributed up to 70%. The reason behind that is a larger composition of MWF, which is made up of 15% of vegetal fatty acid or 30% of mineral oil. Similarly, electricity generation in MQL condition was contributed up to 70% for LO. However, MQL hasn't created a larger impact on LO. Because it uses a very small amount of MWF compared with flood lubrication. Moreover, it was mentioned that the higher impact on LO by electricity is due to the use of wood components for its generation process. When considering the effect of the production of the tools on LO, it was accounted for less than 3% by drilling tools and it was varied between 2%-10% in milling tools.

Overall, the effect from the production of milling tools is greater than that of drilling tools on the aforementioned three impact categories, abiotic resources depletion, climate change and land use. Hence it can be concluded that the impact on the environment from milling cutting tools is higher.

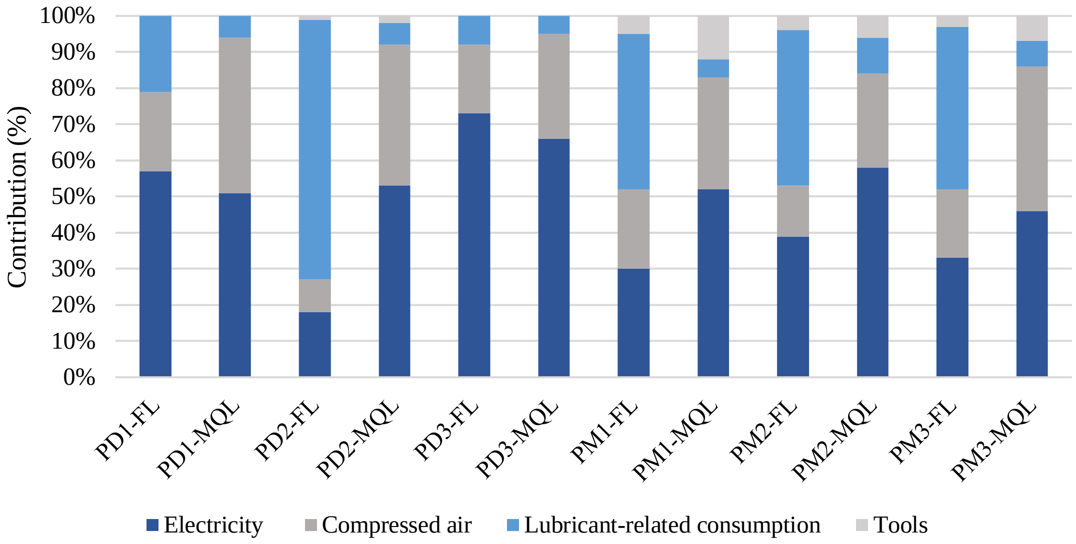

Figure 2-8: The analysed results for land use (Source: [5])

A study was conducted to investigate the contribution to the environmental impact by several cooling methods during turning operation of AISI 304 stainless steel. The functional unit for the LCA was the unit volume of material removed. The MWF production, energy consumption during turning operation, the MWF removing and the process of chip cleaning were considered within the system boundary. The AISI 304 stainless steel production process, MWF treatment process and reuse process of the used materials were considered as the outside processes of the system boundary. It was neglected the generated heat at the cutting region during turning. The environmental impacts due to different cooling techniques were evaluated using the impact assessment method TRACI, based on many assumptions.

In this study, the environmental impact of alternative cooling techniques to flood cooling (wet); dry, MQL and cryogenic lubrication were compared with each other. Based on the results, the authors stated that both dry and MQL conditions are more effective than the cryogenic condition. Moreover, it was mentioned that the feasibility of dry machining for hard-to-cut materials is less due to higher tool wear. But in the environmental point of view, the MQL and cryogenic machining were identified as more efficient alternatives for flood cooling. Furthermore, it was stated that the combination of both MQL and cryogenic conditions may lead to a more sustainable machining operation. The CryoMQL_CO_2 was obtained around 30% increment in tool life compared dry machining. This newly introduced cooling technique, CryoMQL has given lower impacts on the environment and some favourable machining performances; increasing tool life, avoiding the generation of dry chips and reduction of MWF cost. Hence, finally, the authors concluded that the cooling technique, CryoMQL is the most convenient alternative to flood cooling, which can give better performances in the sections of industrial, technical and ecological [78].

2.4.2 Challenges and limitations of life cycle assessment

Even though many studies have been conducted focusing on life cycle assessment (LCA) of machining operations, it was difficult to find a study that considers all relevant aspects. The LCA users have faced many challenges during LCA studies, partially as these methods are still evolving.

To perform LCA accurately and holistically, it is necessary to follow all the four steps as mentioned in standard documents. This is not an easy task, and even though it is a standard method there are some challenges and limitations. Accuracy of the results of any study depends on the accuracy of the input data. It was mentioned that data collection is the most time-consuming task in LCA. The lack of accurate and transparent data sources increases the time taken in data collection. Information on some processes is not yet available even in the most up-to-date databases. There is a high chance of incomplete LCA studies due to unavailability of data [98]. As an example, there is a lack of regionalized data on water systems and physicochemical data [30]. Moreover, even if data is available, there are no clear descriptions about the way data is modelled. Therefore, users have to use the software tools based on different assumptions. Hence, users also fail to validate the accuracy of the results of their studies [103]. Furthermore, models for some impact groups are still in the development stage. The impact categories of biotic resources, land use for transportation, and mining are paid less attention [30].

Uncertainty is the next important factor and this is an area that has not been considered in most LCA studies [103]. However, it is necessary to analyse the uncertainties in LCA studies for a better and more valid interpretation of the results [30]. Uncertainty integration is challenging, and there are several types of uncertainty including data uncertainty, parameter uncertainty, model uncertainty, scenario uncertainty, technical uncertainty, valuation uncertainty, and intra-system variability. Parameter uncertainty has been considered in more studies compared to other types of uncertainties [104].

2.5 Sri Lankan die and mould sector

The Sri Lankan manufacturing sector is used dies with the worth of Rs. 550 million per year. From that, around 45% of dies are manufactured in Sri Lanka while the rest is imported from other countries. These dies are used in different industrial sectors such as metal, plastic, rubber, ceramic and glass. The demand for dies from the aforementioned industries is shown in Figure 2-9.

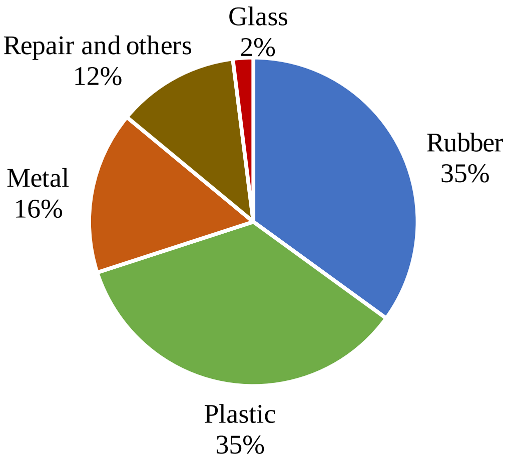

Figure 2-9: Demand for dies from different manufacturing sectors (Source: [105])

Demand for dies with high quality and precision accounts for 90% from total demand for dies. However, the local die and mould manufacturing (DMM) sector can achieve approximately 30% from it. Two of the reasons behind that is the high cost for the die manufacturing process and poor awareness about the global environment [105]. There are two types of costs; direct and indirect cost. Usually, the industries consider the direct cost as the total die manufacturing cost and it consists of cost for raw materials and labour. The indirect cost consists of waste of material during production and extra energy use to achieve the required quality of the mould. The different machining processes are responsible for a higher percentage of additional energy [106]. Hence, even the demand for dies is high in Sri Lanka, the DMM sector is failed to provide at least half of that.

The consumption of energy become high due to the lack of knowledge about different factors which affect energy use. Moreover, most of the DMM centres don’t have sufficient economic background to purchase machines with advanced technology to reduce die manufacturing cost by eliminating additional energy use and reducing reworks. Therefore it is important to find the strategies to overcome those problems using existing facilities [105].

2.6 Summary

The energy and resources consumption for machining purposes are responsible for significant percentages from their global consumption. Moreover, the usage of energy and the MWF during machining are the key sources of its environmental footprint. Hence it is mandatory to find methods to cut down the usage of both energy and MWF during machining. According to the literature, the use of the most convenient cooling technique, cutting parameters and, machining tool leads to reduce the energy consumption during machining. Furthermore, MWF consumption can be reduced by following the most suitable cooling technique.

The standard tool, LCSA is the best strategy for holistic sustainability performance assessment in machining processes. The ISO 14044 standard can be used as a guideline for this approach. However, there are some limitations of this method as it is still in its developing stage, particularly related to the databases of LCA. It is expected that data inventories will improve with time, as this method received widespread attention in the manufacturing sector. Even though several studies have been performed LCA to evaluate sustainability in machining operations, the uncertainty analysis has mostly neglected. It is significant to analyse the uncertainty of an LCA study in terms of data, model, technical or any other term, to obtain a better results interpretation.

The DMM sector largely uses different machining processes during its production process. A larger percentage of die machining is performed by the milling and electrodischarge machining operations. Turning operation is also used to machine some components of a die. Sri Lankan die and mould manufacturing (DMM) sector fails to fulfil the demand for dies in Sri Lankan industries. The higher cost associated with the die manufacturing process is one of the major reasons for that. The hidden cost is caused by additional energy usage and material wastage. Therefore it is important to identify suitable strategies to overcome those issues to cut down the cost, using existing facilities.

A study has evaluated the energy and resource usages of industrial milling operation and proposed optimised cutting parameters considering the Sri Lankan context. Therefore, it is significant to analyse the energy and resource usages of an industrial turning operation. Moreover, there is a lack of life cycle impact assessments carried out concerning the individual contribution of energy and resources in turning. Further, significant process parameters associated with environmental impact have not been comprehensively identified and evaluated. Therefore this research is conducted to bridge the aforementioned research gaps. The findings of this review will be useful to obtain a sustainable turning operation in the DMM sector.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter firstly describes the way of addressing research objectives through different data collection methods. Next, it presents the methodologies of the literature review, background study and experimental study of the research.

3.1 Data collection methods

The research objectives were achieved through literature review, background study, research experiments and environmental performance analysis. The objectives mapping process with data collection methods is summarised in Table 3-1.

Table 3-1: Mapping of objectives with data collection methods

Research objectives	**Address through**
1. To identify the main factors, which affect the environment during turning operation	▪ Literature ▪ Background study (Question numbers 2, 3, 5, 6, 7 and 9 in the questionnaire)
2. To measure and evaluate the effect of change of process parameters on the environmental impact	▪ Experiments ▪ Environmental performance analysis
3. To identify the relationship between machining performances and environmental impact	▪ Experiments ▪ Environmental performance analysis
4. To analyse and compare the environmental impact of industrial turning operation with optimized operation	▪ Environmental performance analysis

3.2 Review methodology

An approach of consistently identifying and analysing the existing knowledge relevant to a particular research area can be considered as a literature review [38]. Hence, a meaningful literature review should reflect may characteristics; a strong foundation for the research topic, research methodology selection, methodologically analysing literature and demonstrating the research findings with some novel aspects [107].

The methodology followed for the literature review consists of four phases. In the initial phase, the purpose of conducting this review was identified. In the second phase, research publications were screened and prioritised by considering the following criteria.

- Keywords – The publications were searched from Elsevier, Springer, Google Scholar, Academia and ResearchGate databases using different keywords; commercial turning, sustainable machining, life cycle assessment, energy consumption during turning, metalworking fluid consumption during turning, parameter optimisation, flood lubrication, dry machining, minimum quantity lubrication, high pressure jet assisted machining, solid lubrication and cryogenic lubrication
- Sources – A higher priority was given to the articles that have been published in journals with high impact factors and proceedings of reputed conferences related to sustainable manufacturing.
- Year of publishing –High priority was given to the papers that have been published in recent years. In summary, the distribution of the selected research papers over recent years is shown in Figure 3-1.

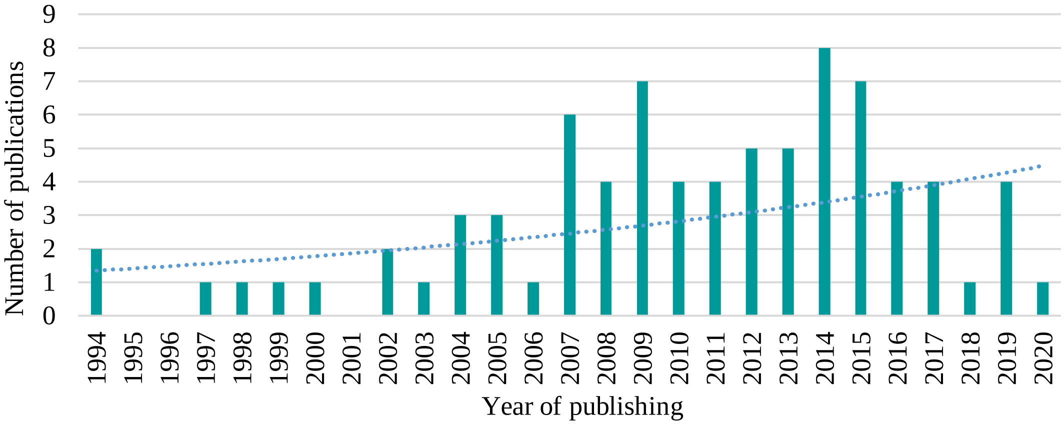

Figure 3-1: Distribution of the selected research papers over the years

The selected publications describe different areas in sustainable manufacturing, focusing on aspects such as critical review of information, experiments, case studies, numerical modelling, and neural network modelling. Those publications are based on sustainability evaluations of machining operations, life cycle assessment (standards, assessment methods, and barriers), sustainable machining (review of strategies), sustainable manufacturing (reviews on opportunities and challenges), and energy consumption patterns during machining operations, as illustrated in Figure 3-2.

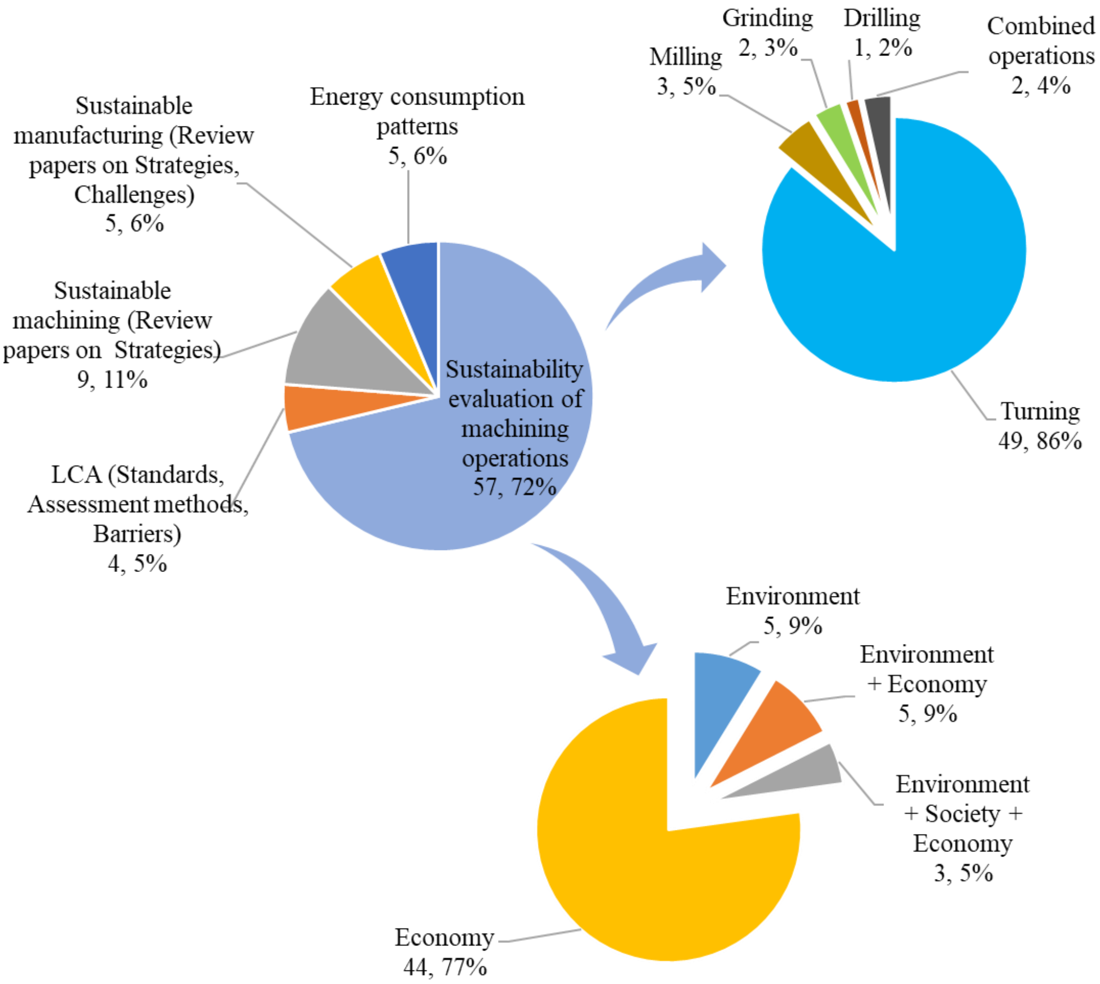

Figure 3-2: Summary of selected publications for the study

The highest fraction of publications, amounting to 72% from selected publications (57 papers), described the sustainability evaluation of machining operations, and out of this, the majority are turning-based studies. Moreover, these publications have focused on the sustainability of machining operations under the three pillars of triple bottom line sustainability; environment, society, and economy. However, it was difficult to find out a study that combined all pertinent aspects of life cycle thinking based holistic sustainability of machining operation. Most of the studies in the literature were focused only on economic improvements of machining operations (44 publications out of 57), in terms of cutting force, surface roughness, tool wear, material removal rate, and machining cost. The least fraction of papers has focused on the impacts on the environment, society, and economy together, equaling 5%. Therefore, it is clear that there is a research gap related to assessment of sustainability aspects of turning operation, in particular, environmental impacts. Hence, the literature review was continued to identify the sources of environmental impact during turning operation and strategies to reduce them.

In the third phase of the methodology, the information in literature was thematically coded using the Microsoft Excel software as described in section 4.1. In the final phase of the literature review, the strategies to reduce identified sources of environmental impact were identified and analysed.

3.3 Background study

A background study was done to justify the applicability of literature context within Sri Lankan die and mould manufacturing (DMM) sector. Out of many DMM facilities located across the country, five independent centres were selected within the proximity considering research cost and access permissions. These facilities sufficiently represent a fair cross-section of the industry in terms of capacity and technology. Those five facilities (A, B, C, D, and E), were used to collect the data through the semi-structured interviews. The questions were made to gather the information related to machining modes, commonly used lathe operations and materials, usage of cooling techniques and average MWF consumption for commercial turning operation per day. The data were gathered in the form of one-to-one interviews in shop floors with lathe machine operators.

I. Commonly used lathe operations

The DMM sector uses several common lathe operations such as turning, facing, parting, grooving, boring and thread cutting. But their level of usage and hence contribution to the total energy consumption during turning operation is varying. The modified digital logic (MDL) method was used to obtain usage of each lathe operations as percentages.

II. Commonly used materials

The usage of different materials for the production of dies depends on the company. The companies, A, B, and C use six types of materials while D and E use five types of materials. There are twelve types of materials; AISI P20, Mild steel, Bright steel, AISI

304, Copper, Bronze, AISI D2, Aluminium, EN19, Cast iron, Carbon steel and Brass. The MDL method was used to obtain the percentages of usage in each company.

III. Commonly used cooling techniques

Most of the die and mould sectors in Sri Lanka uses two cooling techniques wet machining and dry machining during turning. In case companies, wet machining is applied for the turning operation of AISI P20, Mild steel, Bright steel, AISI 304, Copper, AISI D2, Aluminium, EN19, Carbon steel and Brass, while dry machining is used for only Bronze and Cast iron. Hence their usage in each company was analysed.

IV. Machining modes

The lathe machines in DMM sectors are operated under three modes; ON, OFF and STANDBY. The number of hours which the machines are operated under the aforementioned modes within working hours per day was calculated. The lathe machines in companies A, C and D are operated under STANDBY mode at non-machining periods. But in companies B and E, the lathe machines are powered off during that time. Therefore the number of hours which the machines are operated under different modes were obtained as percentages concerning the total number of working hours per day.

V. Metalworking fluid consumption

The data of MWF usage were gathered and analysed to consolidate their actual impact on the environment as mentioned in the literature. There were three manual and one CNC lathe machines in company A, one manual machine in companies B and E, and one CNC machine in company C. MWF consumption in company D was not considered, as there were no reliable sources of information. It was calculated the amount of consumed MWF per hour by considering the volume of MWF tank, topping-up volume of MWF and actual machining time per day.

3.4 Experimental study

3.4.1 Design of experiments

Based on the information gathered through the literature and questionnaire survey in die and mould manufacturing sector the experiments were designed. The energy and metal MWF consumption during turning operation of AISI P20 which uses commonly used cutting parameters under wet and dry machining conditions were measured. A confirmation test was conducted after analyzing data to identify the most preferable cutting parameters within their practised range. The experimental plan is shown in Figure 3-3.

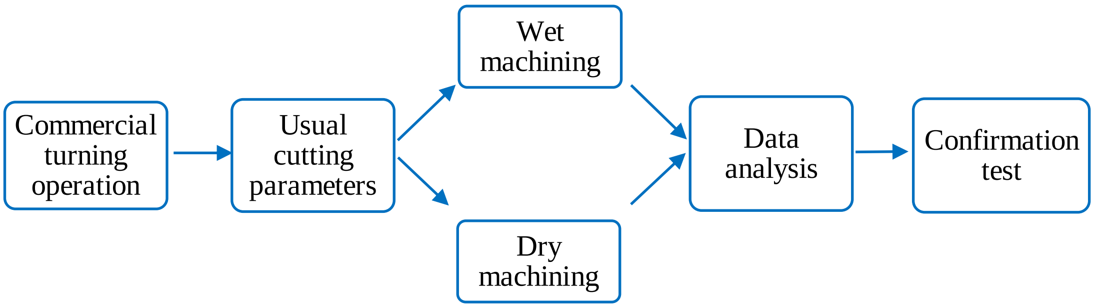

Figure 3-3: Experimental plan

3.4.2 Selection of tool insert and cutting parameters

I. Commonly used tool inserts and cutting parameters in the literature

The three cutting parameters, spindle speed (n), feed rate (f), and, depth of cut (a_p), have been used as the control parameters during turning operation in literature. The 'spindle speed (n)' depends on both the tool insert and the diameter of the workpiece. Hence, literature entries were analysed to identify the most commonly used tool insert type and the practised range of a_p and f during turning of AISI P20. The summary of literature entries is shown in Table 3-2.

Table 3-2: Summary of commonly used cutting insert types and most practised cutting parameters during turning operation of AISI P20

Turning operation	**Cutting insert type**	**Cutting parameters**		**References**
		Depth of cut (mm)	**Feed rate (mm/rev)**	
Straight turning	CVD[1]	0.5	0.5	[108] [109] [110]
High-speed turning	PCBN[2]	0.20, 0.25, 0.30	0.1, 0.15, 0.2	[111]
Straight turning	CVD, PVD[3]	1.0 , 1.5, 2.0	0.12, 0.18, 0.22	[112]
Orthogonal end turning	Uncoated tungsten carbide	2.4	0.025, 0.051	[113]
Straight turning	CVD	1.0, 1.5, 2.0	0.005, 0.04, 0.06, 0.08, 0.09, 0.10, 0.13, 0.23	[114]
High-speed turning	CVD	0.20, 0.35, 0.50	0.10, 0.12, 0.14	[115] [52] [116]
Straight turning	CVD	0.05, 0.10, 0.175	0.12, 0.14, 0.16	[117]

According to the summary in Table 3-2, the cutting inserts with CVD coating have been used mostly in literature. The usage of cutting parameters depends on the turning operation. The ranges of both a_p and f are varied in a narrow region for high-speed turning, while those for the straight turning have wider ranges. The range of a_p for high-speed turning is 0.20 - 0.50 mm, and for straight turning is 0.05 - 2.00 mm. The range of f high-speed turning is 0.10 - 0.20 mm/rev, and for straight turning is 0.005 - 0.23 mm/rev.

II. Tool insert

A survey has been conducted by Senevirathne [105] to identify the most common cutting tool used in the die and mould manufacturing sector. The results of this survey show that the tool brand “Mitsubishi” is used mostly. According to the summary in Table 3-2 and survey results in [105], one of the recommended tool inserts for AISI

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[1] CVD: Chemical Vapour Deposition

[2] PCBN: Polycrystalline Cubic Boron Nitride

[3] PVD: Physical Vapor Deposition

P20, Mitsubishi TCMT16T304 CVD coated carbide (UE6110), was selected for experiments. The geometry of that tool insert is shown in Figure 3-4.

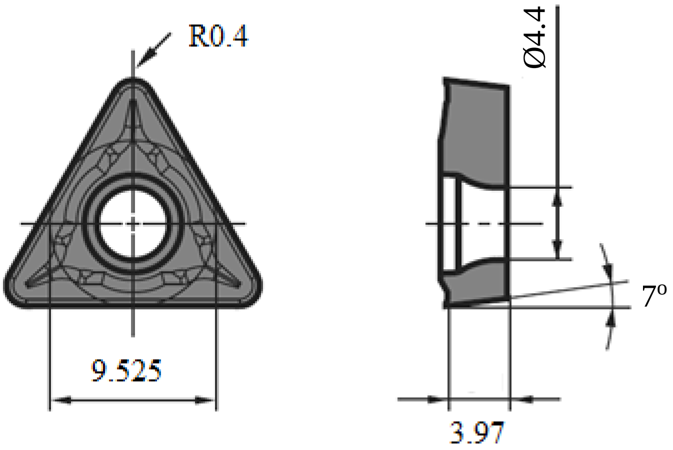

Figure 3-4: Geometry of the tool insert (all dimensions are in mm)

III. Cutting parameters

The tool insert's manufacturer-recommended cutting speed range for turning of AISI P20 is 160 - 270 m/min. Hence, the three cutting speeds, 189 m/min, 215 m/min and 241 m/min were selected. To select the other two cutting parameters depth of cut (a_p) and feed rate (f), both recommendation of the tool insert's manufacturer and literature entries were considered. Figure 3-5 illustrates the recommended range of both " a_p" and " f " during turning using 7° positive tool insert [118].

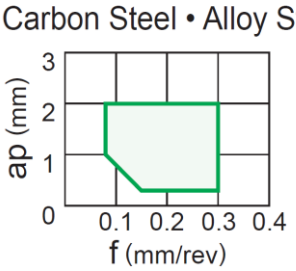

Figure 3-5: The Mitsubishi tool insert manufacturer-recommended depth of cut (a_p) and feed rate (f) ranges for turning (Source: [118])

According to Figure 3-5, the typical ranges of a_p is 0.3 – 2 mm, and f is 0.08 – 0.3 mm/rev. The recommended and practised value regions of a_p and f and are shown in Figure 3-6.

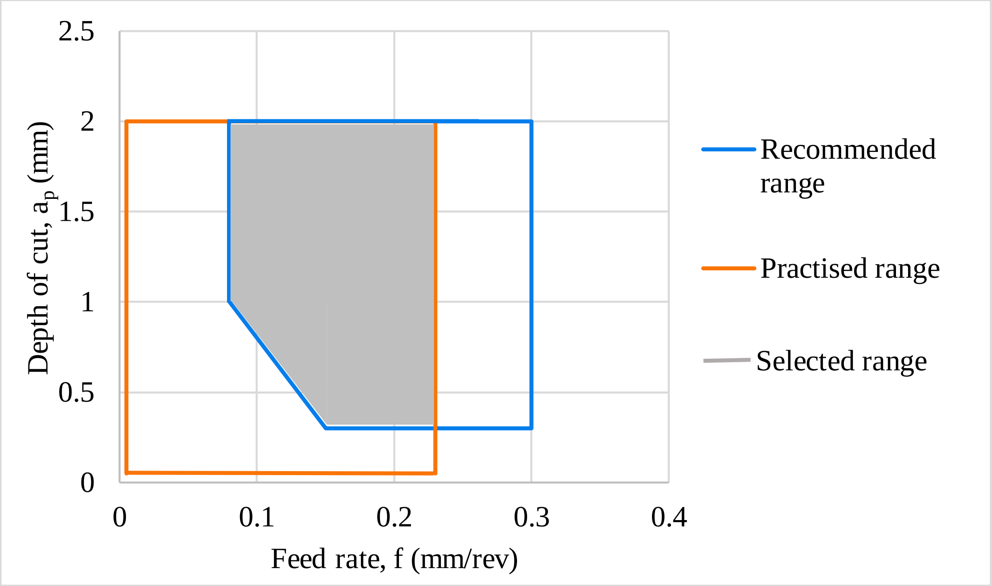

Figure 3-6: The recommended and practised values of feed rate and depth of cut

Considering both literature and the recommended values of a_p and f, the following cutting parameters in Table 3-3 were selected for the straight medium turning operation of AISI P20.

Table 3-3: Summary of selected cutting parameters

Cutting parameters	**Selected range**	**Selected values**		
		Level 1	**Level 2**	**Level 3**
Cutting speed, V_c (m/min)	160 - 270	189	215	241
Spindle speed, n (rev/min)	728 - 1228	860	980	1100
Feed rate, f (mm/rev)	0.08 - 0.23	0.10	0.15	0.20
Depth of cut, a_p (mm)	0.30 – 2.00	0.55	1.10	1.65

3.4.3 Workpiece

According to the results of the questionnaire survey in die and mould manufacturing sector, the AISI P20 is the most commonly used material. Therefore it was selected as the workpiece material for the experiments. All together 10 number of workpieces with the diameter of 35mm and the length of 100 mm as illustrated in Figure 3-7 was used for the experiments. Due to the less material availability, 40 mm length was selected as the machining length.

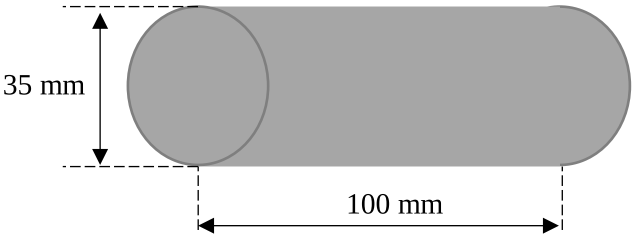

Figure 3-7: Workpiece with dimensions

The range of chemical composition of AISI P20 is shown in Table 3-4. The actual chemical composition of workpiece materials used for the research experiments is shown in Table 3-5. This was identified through a material test which was performed in the Department of Materials Science and Engineering, University of Moratuwa. The chemical composition of sample material was analysed based on how it absorbs light in the infrared part of the spectrum. The absorption of infrared light is directly related to the bonds present in various molecules.

Table 3-4: The range of chemical composition of AISI P20 (percentages in weight, %wt) [119]

Cr	Mn	C	Si	Mo	Fe
1.40-2.00	0.60-1.00	0.28-0.40	0.20-0.80	0.30-0.55	Balance

Table 3-5: The actual chemical composition of AISI P20 used for the research experiments (percentages in weight, %wt)

Cr	Mn	C	Si	Mo	Fe
1.85	0.82	0.39	0.45	0.37	95.85

As literature says, the specific volume of material removed is a better reference flow compared with one-second machining process [99]. Hence to remove a constant volume of material in each experiment, the diameter of the workpiece was reduced from 35 mm to 28.4 mm. The removed volume of material is 13145.68 mm^3.

3.4.4 Taguchi L_9 orthogonal array

The number of optimisation techniques such as Taguchi methodology, Multiple regression analysis, Response surface methodology (RSM) [71], Artificial neural network and Full factorial analysis was evident in the literature. The Taguchi methodology is the most practised optimisation technique than other techniques [72]. A literature survey has been performed to identify the widely used optimisation method for machining performance, surface roughness. The survey results show that the Taguchi optimisation method has used widely compared with other techniques as illustrated in Figure 3-8 for reasons such as easily understandable theory, less number of experiments, and economic benefits [120].

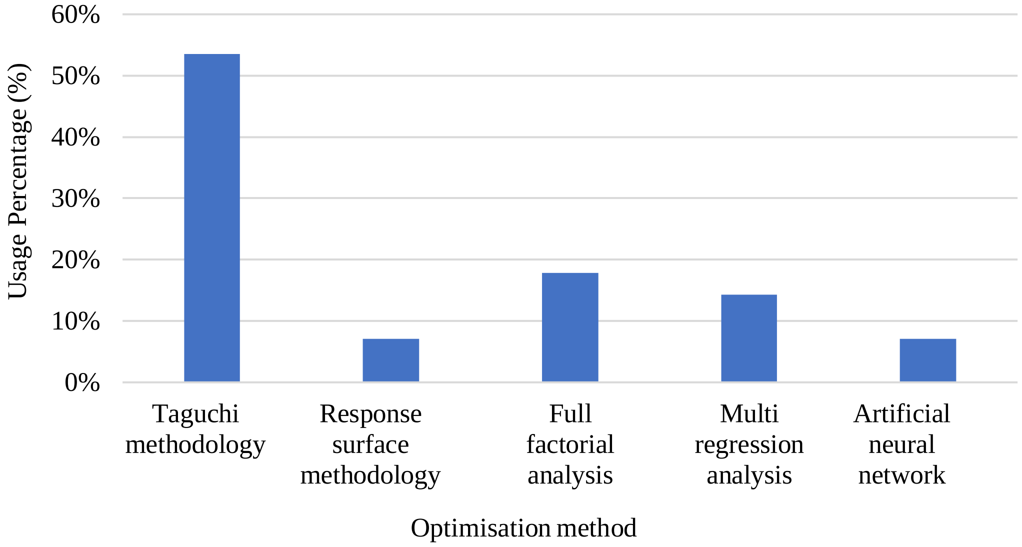

Figure 3-8: Usage of optimisation techniques for surface roughness in literature (Source: [120])

Furthermore, in Table 2-3, fifth column consisting of the analyzing methods used to identify the most influencing parameter on energy consumption during turning of different materials. Two design of experiments (DOE) techniques, Taguchi and RSM have been used in literature. However, the larger percentages of papers (7 publications out of 10), were used Taguchi technique as illustrated in Figure 3-9. Therefore it is obvious that the Taguchi technique is the frequently used DOE technique.

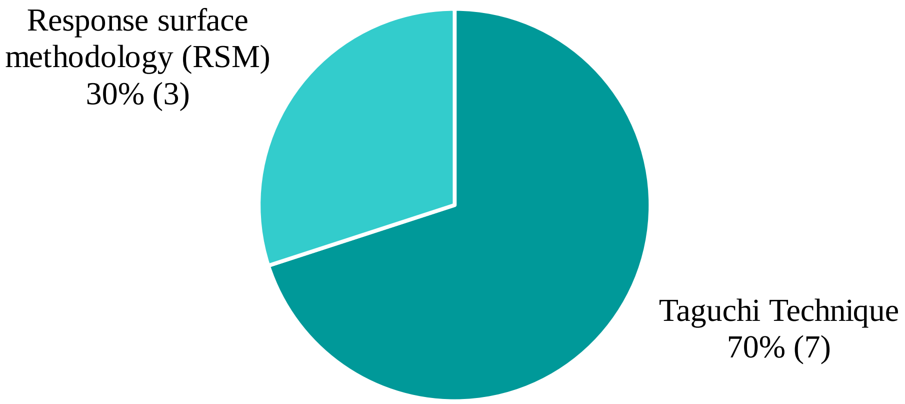

Figure 3-9: Design of experiment techniques usage in the literature

Hence, the DOE was obtained using the Taguchi methodology. The cutting parameters, spindle speed (n), feed rate (f), and depth of cut (a_p) were chosen as variable parameters and the Taguchi L_9 orthogonal array was obtained as shown in Table 3-6.

Table 3-6: Taguchi L_9 orthogonal array design for the experiments

Array No.	Parameters' values			Parameters' levels		
	n	f	a_p	n	f	a_p
1	860	0.10	0.55	1	1	1
2	860	0.15	1.10	1	2	2
3	860	0.20	1.65	1	3	3
4	980	0.10	1.10	2	1	2
5	980	0.15	1.65	2	2	3
6	980	0.20	0.55	2	3	1
7	1100	0.10	1.65	3	1	3
8	1100	0.15	0.55	3	2	1
9	1100	0.20	1.10	3	3	2

The experiments were conducted under two machining conditions based on the lubrication technique; wet and dry machining. Hence, the same L_9 orthogonal array design was used for both machining conditions. Therefore, 18 number of experiments were conducted as summarized in Table 3-7.

Table 3-7: Summary of experiments under two machining conditions

Operating condition	**Experiment Number**	
	Wet machining	**Dry machining**
1	E1	E10
2	E2	E11
3	E3	E12
4	E4	E13
5	E5	E14
6	E6	E15
7	E7	E16
8	E8	E17
9	E9	E18

3.4.5 Experiment arrangements

This section describes the methodologies of measuring electric energy consumption, MWF consumption, surface roughness, and material removal rate during the experiments.

I. Measuring energy consumption

The energy consumption during the turning operation was measured using FLUKE 1736 power logger. The FLUKE 1736 power logger was coupled to the three-phase electricity connection using 3-ϕ Wye configuration as shown in Figure 3-10. The power logger was coupled through the panel board of CNC lathe machine and mini circuit breaker of air conditioning (AC) system as shown in Figure 3-11, to measure their electricity consumption during turning.

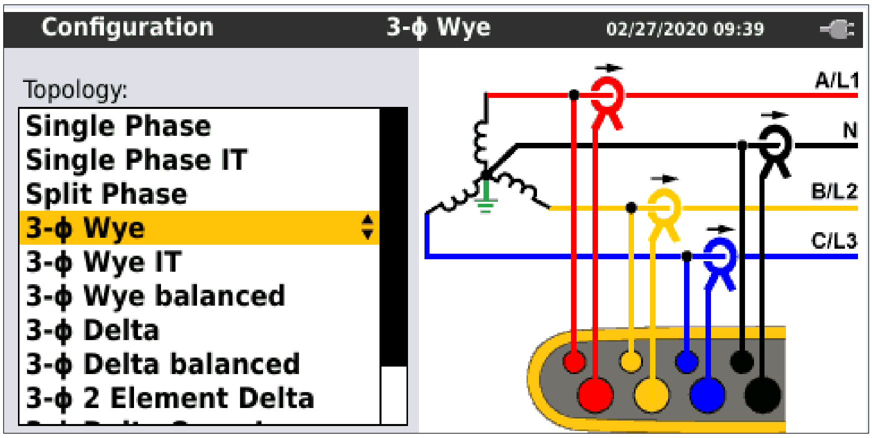

Figure 3-10: 3-ϕ Wye configuration

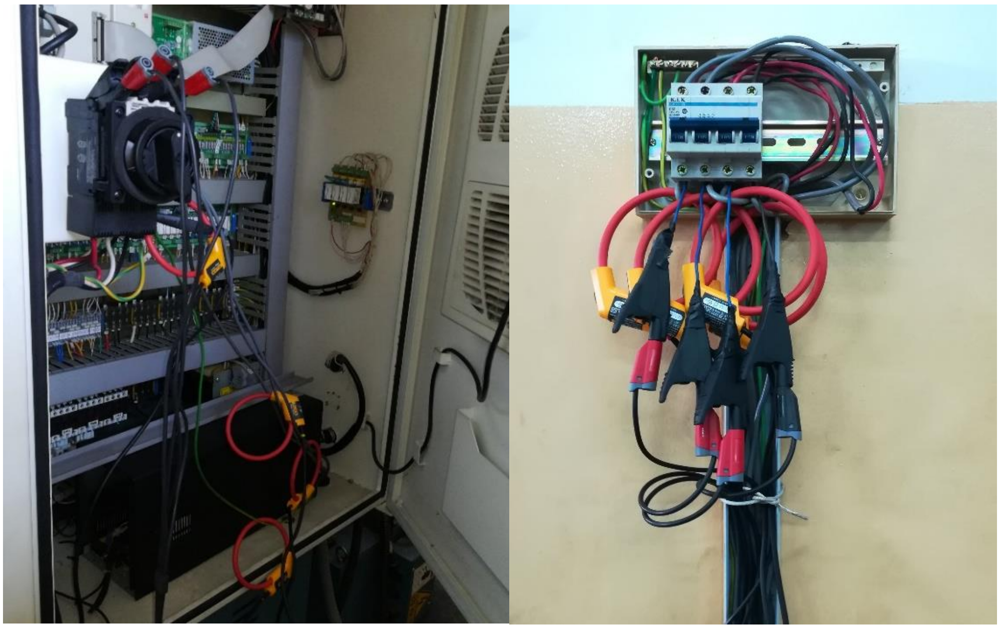

Figure 3-11: Coupling of FLUKE 1736 power logger through the panel board of CNC lathe machine (left) and mini circuit breaker of air conditioning system (right)

All the lights in the machining centre were powered on during all the working time. Furthermore, lighting has consumed between 9.5% and 29.1% of the overheads electricity consumption in industries [121]. Hence, electricity consumption for lighting was calculated considering product specifications of lights, floor area of the machining centre and CNC lathe machine.

II. Measuring the metalworking fluid consumption

A mixture of EcoCool 700 NBF M (5%) and water (95%) was used as the MWF in the CNC lathe machine used for the experiments. The top-up volume of MWF was calculated considering the actual cutting time and top-up rate. It was considered as the MWF consumption during machining. Furthermore, by considering the top-up volume and the disposed volume of MWF for one-hour turning operation, amounts of MWF consumed during each experiment was calculated.

III. Measuring the surface roughness

The arithmetical mean surface roughness (Ra) is an effective and commonly used indicator in the industry to evaluate the quality of the machined area [33] [122]. Ra of the machined surface was measured using the Mitutoyo SJ-301 surface roughness tester having the resolution, 0.01 µm as illustrated in Figure 3-12. While measuring the Ra, 2.5 mm and 20 mm were selected as the cut-off length (λ) and evaluation length respectively. Three values Ra were taken on three locations of the periphery of the machined area as shown in Figure 3-13. Then the average value of three measurements was considered as the average Ra.

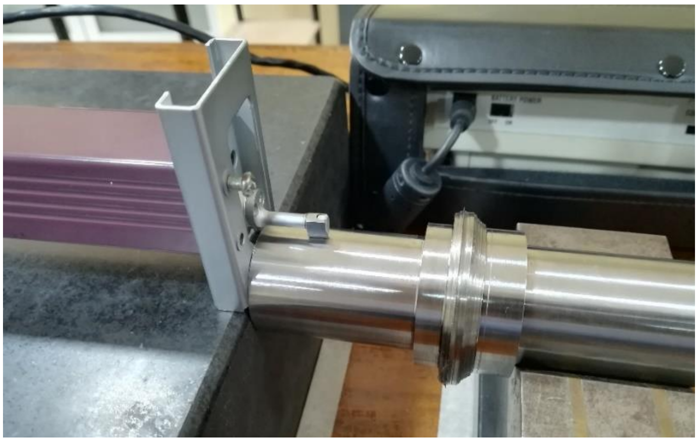

Figure 3-12: Measuring the surface roughness of the machined area

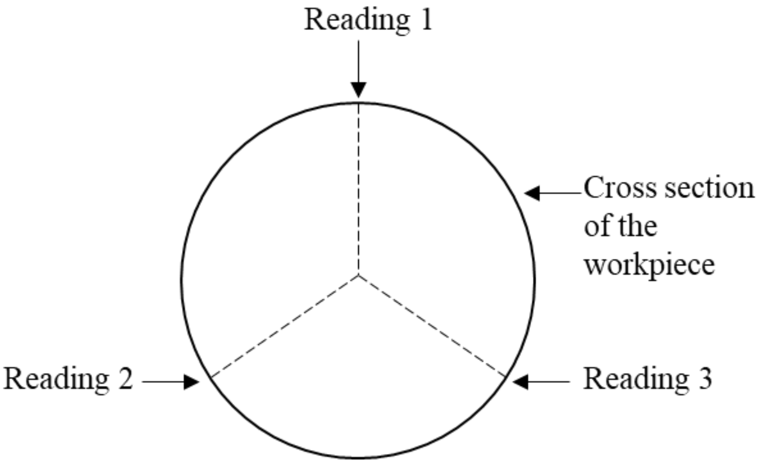

Figure 3-13: Three locations around the periphery of the machined area

IV. Measuring the material removal rate

The constant volume of material removed (13145. 68 mm^3) was kept as the reference flow. The time for actual machining (turning) operation in each experiment was identified from power logger data. Then the material removal rates (MRR) were calculated.

CHAPTER 4 DATA ANALYSIS

The data were gathered in three forms; literature, interviews in background study and observations, data recordings, and measurements during research experiments. The gathered data were analysed using different software tools and analyzing methods as mentioned below.

4.1 Analysis of literature using Microsoft Excel

The Microsoft Excel software was used to thematically code the information in the literature. The literature context was analysed under different themes as shown in Figure 4-1. Meanings of different main themes and sub-themes based on their content are briefly described below.

- Sustainable manufacturing –Information under this theme were divided into three sub-themes as follows.
    - Importance – This sub-theme consists of the information in the literature that provides shreds of evidence for the definitions of sustainable manufacturing and its significance in various industries.
    - Sustainable principles – This contains the information regarding the three pillars of sustainability and key evaluation areas in sustainable manufacturing.
    - Limitations – Difficulties faced by different industries while following sustainable principles were gathered under this sub-theme.
- Environmental impacts – Information in the literature relevant to the environmental impacts during the turning operation were categorized under following sub-themes.
    - Standards and evaluation tools – Details about the international standards established by ISO for environmental management, regulations made by organizations in various countries to enhance the practices of sustainable machining and different environmental impact evaluation tools.
    - Sources – This sub-theme consists of information about the different sources of environmental impacts during different machining operations.

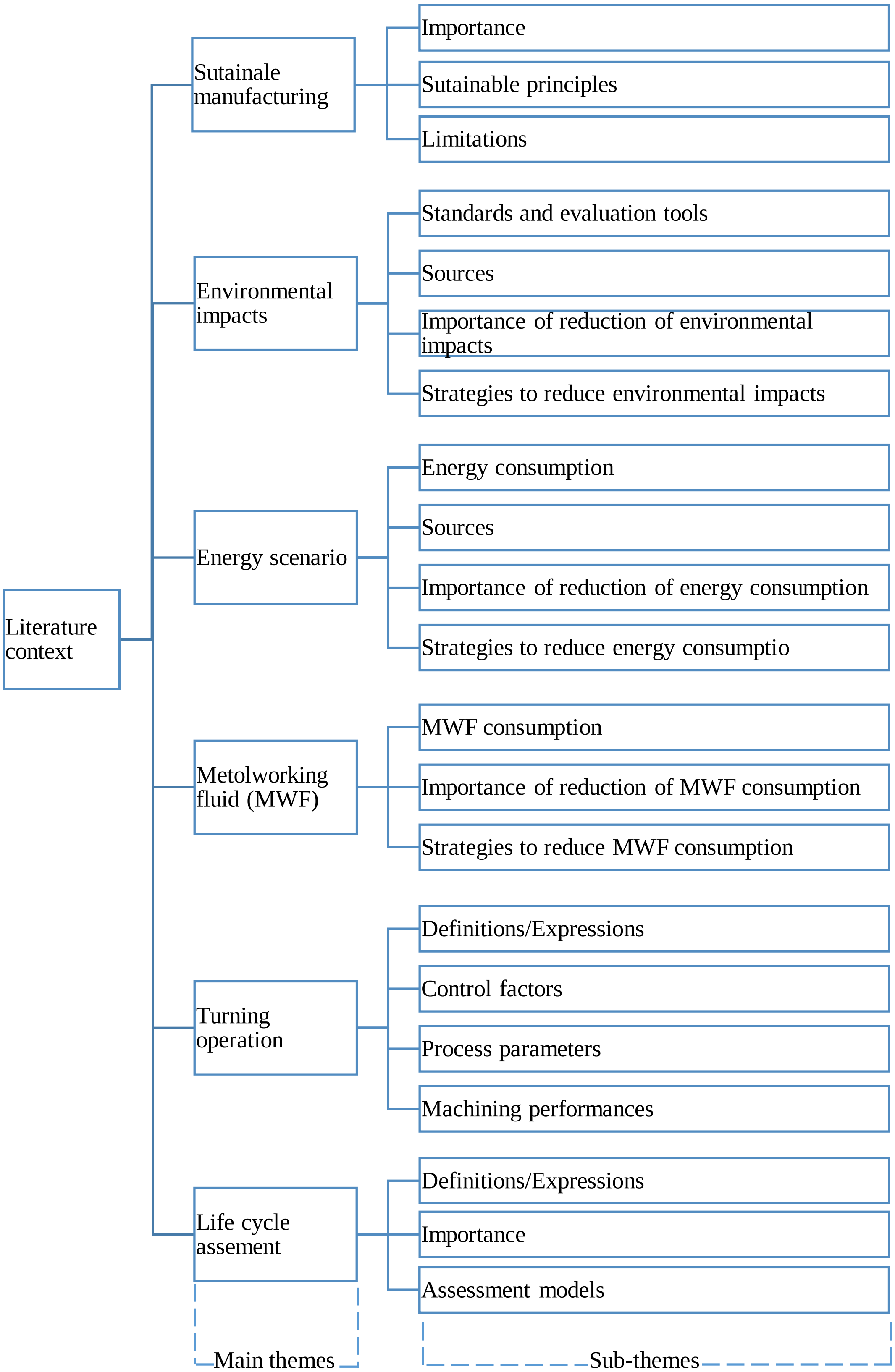

Figure 4-1: Different themes used to analyse the literature context

    - Importance of reduction of environmental impacts – This consists of information about the number of improvements which the manufacturing sector can be obtained through environmental impacts reduction.
    - Strategies to reduce environmental impacts – Details about the number of strategies mentioned in the literature to mitigate the environmental problems during machining.
- Energy scenario – Data related to the energy consumption in industry sector were divided under the following four sub-themes.
    - Energy Consumption – Statistical data of energy consumption in the world, manufacturing sector and various machining operations were gathered under this sub-theme.
    - Sources – Sources of energy consumption during machining, especially in turning operation were considered under this sub-theme.
    - Importance of reduction of energy consumption – This sub-theme consists of the significance of energy consumption reduction and its advantages on the industry sector.
    - Strategies to reduce energy consumption – Information about the number of strategies stated in the literature to reduce energy consumption during the turning operation were collected under this sub-theme.
- Metalworking fluid (MWF) – Information relevant to this main theme were categorized under three sub-themes as follows.
    - MWF consumption – This consists of statistical data of MWF consumption for machining purposes and patterns of MWF consumption in different lubrication/cooling techniques.
    - Importance of reduction of MWF consumption – This consists of the details about both direct and indirect impacts of MWF consumption during machining operations and the significance of the reduction of MWF consumption.
    - Strategies to reduce MWF consumption – This consists of information about various strategies used in the literature to cut down the amount of MWF consume during cooling/lubrication.

- Turning operation – Information about the turning operation were categorized using the following sub-themes.
    - Definitions/ Expressions – This consists of the definitions of the turning operation, process parameters and importance of turning operation in the manufacturing sector.
    - Control factors - Details about the factors/parameters which affect the excellence and cost of the process were collected under this sub-theme.
    - Process Parameters – Details about the key process parameters such as cutting speed, depth of cut and feed rate were gathered under this sub-theme.
    - Machining Performances – This consists of the information about the number of machining performances used to address the quality of turning operation in literature.
- Life cycle assessment (LCA) – Information about the LCA in literature was divided under following sub-themes.
    - Definitions/ Expressions – Definitions about different terms use in the LCA such as normalisation, weighting, impact categories, uncertainty, etc. were collected under this sub-theme.
    - Importance – This consists of details about the significance of LCA in industry, manufacturing sector and especially in machining.
    - Limitations – Information about the challenges faced by practitioners during LCA studies were gathered under this sub-theme.
    - Assessment models – This sub-theme consists of details about various assessment models use in LCA.

4.2 Analysis of interview replies using the modified digital logic method

The modified digital logic (MDL) method was employed to analyse the usage of lathe operations and materials in die and mould manufacturing sector. The MDL method can give a quantitative value for their usage. According to the MDL method, the usage of one parameter (lathe operation or material) was compared with another parameter. It has assigned values based on their relative usage. If the usage of a parameter is higher than another parameter, the assigned value is 3. If it is less, the assigned value is 1 and if it is equal the assigned value is 2. If the number of parameters is n, the number of possible decisions (N) can be calculated using Equation 4-1.

$$N = \frac{n(n-1)}{2} \qquad \text{Equation 4-1}$$

The summation of assigned numerical values for each possible decisions for each parameter is known as a positive decision. Then the weighting factor, α, can be obtained following Equation 4-2.

$$\alpha = \frac{Positive\ decision\ for\ one\ parameter}{Total\ number\ of\ positive\ decisions} \qquad \text{Equation 4-2}$$

In this analysis session, the α was considered as value for the usage of different parameters [123]. Then multiplying α by 100, the percentages of usage were obtained.

4.3 Experimental data analysis

4.3.1 Energy consumption analysis

The pattern of energy consumption of 'Tour ARIX TNC 430 CNC' lathe machine during turning of AISI P20 in experiment no 01 is shown in Figure 4-2. It can be observed that the STANDBY power is 0.85 ± 0.02 kW. As per [124] this could be due to the energy required to start-up the lathe machine, hydraulic pump, computer unit, unload motors, light system and constant power consumption of the lubricating pump. However, in the sixth minute (06:24), there is an initial surge of power (Figure 4-2 – label 'P') is due to the additional power consumption of the spindle for acceleration from zero to a higher speed (860 rpm in experiment no 1) and this also agrees with past studies [125]. The motor, motor drive and mechanical transmission are the components of the spindle system [126]. The expanded view of power consumption during the period of spindle acceleration is shown in Figure 4-3.

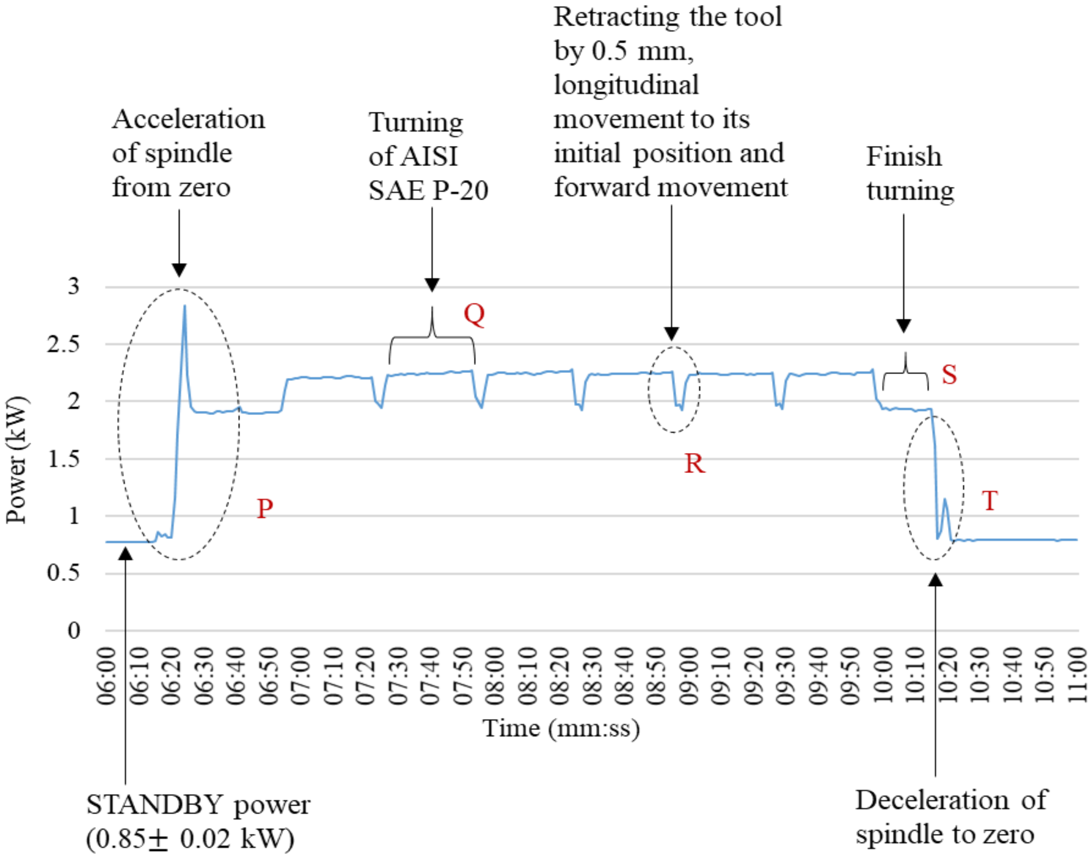

Figure 4-2: Energy consumption pattern by the CNC lathe machine during turning operation

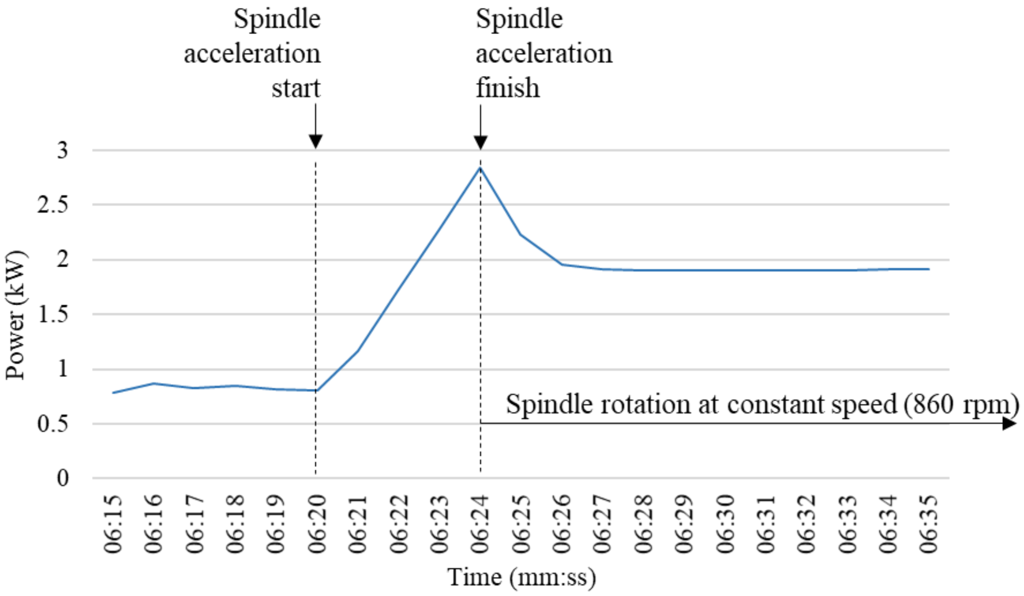

Figure 4-3: Power consumption by the CNC lathe machine during spindle acceleration

The repeating wave pattern in Figure 4-2 (label ‘Q’) corresponds to each pass of the turning operation. During one pass, the tool moves the length of 40 mm to the direction which is parallel to the axis of rotation of workpiece, or from point A to B in Figure 4-4, by reducing 1.1 mm from workpiece diameter. The average power consumption. Jogs (X, Y, Z), spindle motor, drives and coolant pump are the main components which are responsible for this increase in power consumption. Furthermore, additional power is required for the material removing process [127].

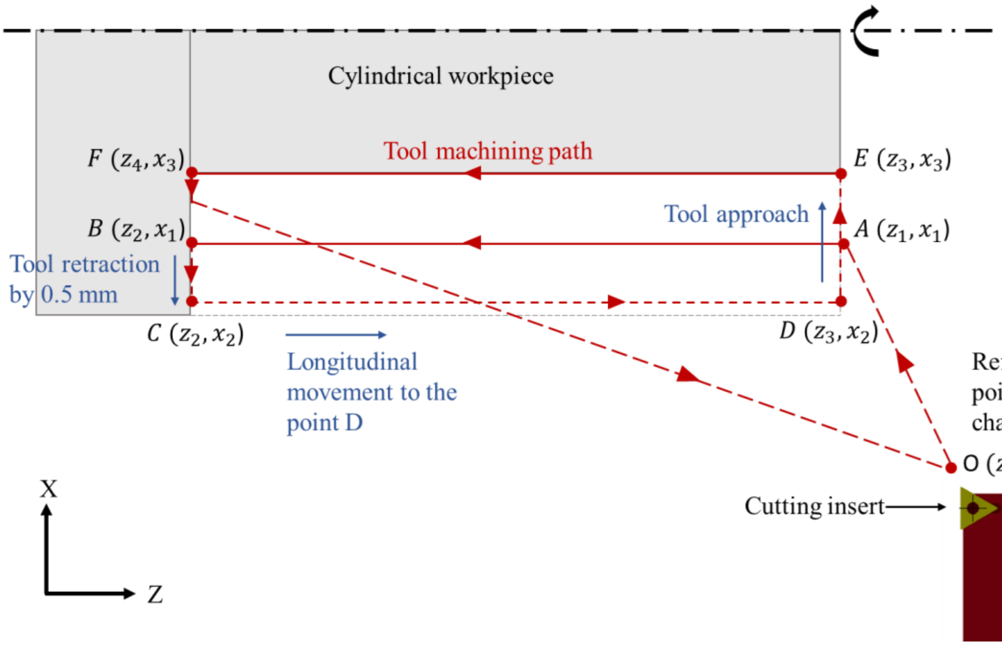

Figure 4-4: Tool moving path during turning operation

The sudden decrement between each wave (label ‘R’) is due to the retracting of the tool by 0.5 mm away from the workpiece (from point B to C) as demonstrated by Figure 4-4. At that time the power consumption is directly reduced due to the absence of the material removing process. Then the tool moves longitudinally to point D and it takes around two seconds. After that, the tool approaches the workpiece within one second. After the coarse turning operation, a finish turning process is done. The average power consumption during finish turning is comparatively lower than during rough turning as shown in Figure 4-2 – label ‘S’. This is further validated from the literature [24]. The sudden fall after the finish turning (label ‘T’) corresponds to the deceleration of spindle. The patterns of power consumption during each experiment are attached as Appendix B.

The turning time is two fold, machining time (t_m) and non-machining time (t_{nm}). Machining time includes time for changeover the workpieces, spindle acceleration, rough turning, finish turning and spindle deceleration. The energy consumption during machining time is considered as machining energy (E_m). The machining time divides into two groups for the easy of calculation; changeover time (t_{co}) and cutting time (t_c). Summation of machine set-up period, operator waiting period and finishing-up period are taken as non-machining time [128]. Energy consumption during those periods is considered as non-machining energy (E_{nm}).

Both t_m and t_{nm} of CNC lathe machine per working hour were calculated using power logger data. The calculated values of t_m and t_{nm} are 1,494 sec (41%) and 2,106 sec (59%) respectively. During t_{nm}, the lathe machine operates under STANDBY mode. Hence, the E_{nm} for one-hour turning operation is 0.50 kWh. The t_{co} depends on the operator. Moreover, due to the variation of the operator waiting period, t_{co} of workpieces are varied. Hence, the average t_{co} (577 sec) was calculated. However, it is unreasonable to consider that the entirety of this t_{co} was utilized for changeover, because it also includes some operator waiting time. As stated in the literature, around 10% from the time is wasted due to the technical problems (waiting and delays) during work [129]. Therefore, 519 sec is utilized for the changeover. Furthermore, ideal labour efficiency during work varies between 85% – 95% [130]. Hence it was assumed that the operator has worked around 90% efficiency. Accordingly, the calculated t_{co} is 467 sec. During the changeover period, the lathe machine operates under STANDBY mode. Therefore, the consumed energy per workpiece during the changeover period (E_{co}) was 0.11 kWh. The t_c per one-hour turning operation is 1027 sec (t_m - t_{co}).

There are two 48000 BTU split type air conditioning (AC) units in the machining centre. The average energy consumed per hour for two AC units is estimated as 6.65 kWh using the power logger data. The total floor area of the machining centre is 93.34 m^2. The floor area for CNC lathe machine including working space is 11.70 m^2. It was assumed that all the machines in the machining centre were working at that time having equal heat loads. Hence the energy consumed per one hour of CNC turning operation by two AC units (E_{ac}) is apportioned as 0.83 kWh.

There are 20 fluorescent 40W tube lights in the machining centre. The total power consumption for one hour is 0.80 kWh. The average energy consumed per hour of CNC turning operation by lighting (E_l) was 0.10 kWh. Due to the inaccessibility of accurate energy use data, the energy consumption for fans and computers in the machining centre is excluded. Hence, for one-hour turning operation, the total energy consumption (E_{total}) was calculated using Equation 4-3.

$$E_{total,n} = E_c + E_{co} + E_{nm} + E_{ac} + E_l \qquad \text{Equation 4-3}$$

Where, $E_{co} = 0.11$ kWh

$E_{nm} = 0.50$ kWh

$E_{ac} = 0.83$ kWh

$E_l = 0.10$ kWh

For experiment number 1, $E_c = 0.64$ kWh

Then the total energy consumption for experiment number 1 is,

$$E_{total,1} = (0.64 + 0.11 + 0.50 + 0.83 + 0.10)kWh$$

$$= 2.18\ kWh$$

The data of energy consumption during each experiment are in the 3rd column of Table 4-1. Then the variation of energy consumption in each experiment with operating conditions was analysed using Microsoft Excel software.

4.3.2 Analysis of MWF consumption, Ra and MRR

The results of the background study in Table 5-1 show that the top-up volume of MWF for 8 hours working shift is 3 Liters. According to the energy study, the machining time percentage for one-hour turning operation is 41 % (1494 sec). It includes 467 sec of average changeover time and 1027 sec of average cutting time. Hence, the top-up rate of MWF during the cutting period of one-hour is 1314.51 ml/hour. The top-up volume of MWF was calculated considering the actual cutting period in each experiment and the summary is tabulated in 4th column of Table 4-1.

The collected data of MWF consumption, Ra (5th column in Table 4-1) and MRR (6th column in Table 4-1) were analysed to identify its variation with respect to each operating condition. The fluctuation Ra and MRR with operating conditions under both wet and dry machining were plotted. The analysis was performed using Microsoft Excel software.

Table 4-1: Summary of experimental data of each experiment

Ex. No	**Operating condition**	**Energy consumed (kWh)**	**MWF consumed (ml)**	**Surface Roughness (µm)**	**MRR (mm^3/s)**
E1	1	2.18	72.66	1.06	66.06
E2	2	2.19	30.67	2.32	156.50
E3	3	2.20	17.53	4.09	273.87
E4	4	2.27	39.07	0.94	122.86
E5	5	2.12	20.08	2.02	239.01
E6	6	2.18	37.97	3.34	126.40
E7	7	2.24	25.56	1.00	187.80
E8	8	2.26	43.09	2.53	111.40
E9	9	2.31	20.45	4.05	234.74
E10	1	2.23	-	1.36	65.73
E11	2	2.26		2.92	166.40
E12	3	2.27		4.31	279.70
E13	4	2.32		1.45	136.93
E14	5	2.30		2.95	248.03
E15	6	2.29		3.98	125.20
E16	7	2.37		2.09	208.66
E17	8	2.29		2.44	111.40
E18	9	2.36		4.02	239.01

4.4 Environmental performance analysis

Environmental performance analysis was performed following the life cycle assessment (LCA) methodology. There are variants of LCA; cradle-to-grave, cradle-to-gate, gate-to-gate, and cradle-to-cradle. To reduce the complexity of LCA and obtain more accurate results using experimental data, the LCA of commercial turning operation under the gate-to-gate variant was selected.

4.4.1 Goal and scope

The goal of LCA is to quantify the environmental impacts of one-hour commercial turning operation due to the use of energy, MWF, workpiece, and tool materials. To achieve the aforementioned goal, the one-hour turning operation was chosen as the functional unit. The schematic representation of the system boundary is shown in Figure 4-5. The observation of energy and resource consumption during commercial turning operation was performed considering the system boundary condition. Wastage of energy as heat during the turning process wasn't evaluated.

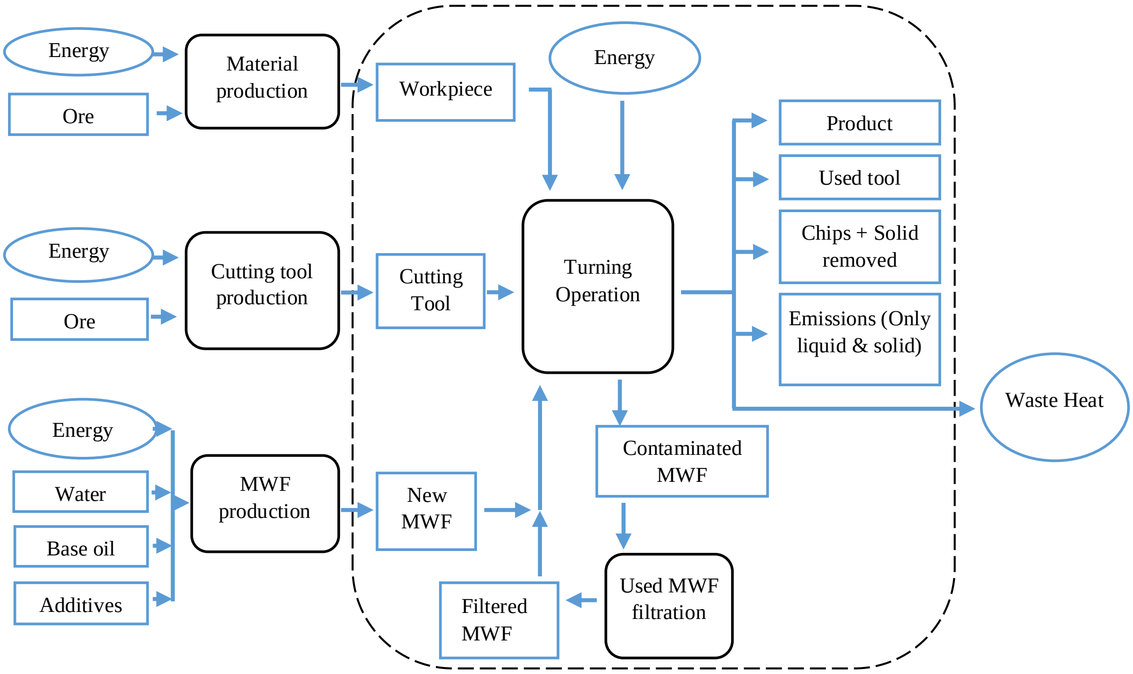

Figure 4-5: Schematic representation of the system boundary

4.4.2 Inventory analysis

For the inventory analysis, the raw materials; workpiece, cutting tool, MWF (EcoCool 700 NBF M and water), and energy were considered as the environmental inputs associated with turning operation. The removed volume of workpiece material was kept as constant and which is 13145.68 mm^3.

The removed volume of tool material is varied with the operating condition. The top surface area of the removed region of tool inserts [131] was measured using SketchAndCalc Area Calculator while the depth was measured using Gwyddion open-source software. The TCMT16T304 CVD coated carbide (UE6110) insert is a Tungsten Carbide (WC) based cutting insert with two Nano-texture coatings of Al_2O_3, TiCN, and Titanium (Ti) compound layers on both rake and flank faces. Densities of the WC is 15.63 g/cm^3 [132] and coating layers is 4.25 g/cm^3 [133]. The calculated equivalent density of cutting insert is 12.00 g/cm^3. Hence, the mass percentage of the base material (WC) is 88.75% and the coating layers is 11.25%. Then the reduced weights of cutting inserts during each experiment were calculated. Tool life of a cutting insert depends on the cutting speed. According to the tool manufacturer-recommended tool life for different cutting speeds, the removed volumes at the end of tool life were estimated. Cutting inserts are disposed to the environment, once they achieved their tool life. Hence, the disposed volumes of cutting inserts under each experiment were estimated and apportioned for the machining time. Finally, the summation of actual removed volume and apportioned volume was taken as input for the LCA.

To obtain the MWF consumption during the one-hour turning operation for LCA, the summation of top-up volume and apportioned disposed volume in each experiment of wet machining was taken. Top-up volume for one-hour turning period is 375 ml. Moreover, around 75 L of MWF is disposed to the environment once a six month. The disposing amount of MWF for a machining hour is 273.86 ml. Hence, the MWF consumed during one-hour turning period is 648.86 ml. The amounts energy consumption were gathered as described in sections 4.3.1.

The environmental outputs of the operation in terms of emissions; to air, soil and, water were estimated using Ecoinvent database and literature. It was assumed that 5% of used MWF was evaporated to the atmosphere [100] and that was considered as emissions to air. The rest of EcoCool 700 NBF M and water in used MWF (95%) were considered as emissions to soil and water respectively. The waste of energy as the heat was not considered as an environmental output. The input and output flows of the inventory for the environmental performance analysis were obtained using the aforementioned data and the summary is shown in Table 4-2.

Table 4-2: Inventory summary

Ex. No	Inputs					Outputs			
	AISI P20 (g)	Energy (kWh)	Cutting insert (g)	EcoCool (g)	Water (g)	Emissions to air		Emissions to soil	Emissions to water
						EcoCool (g)	Water (g)	EcoCool (g)	Water (g)
E1	103.19	2.18	0.66	32.44	616.41	1.62	31.12	30.82	585.29
E2	103.19	2.19	0.66	32.44	616.41	1.62	31.12	30.82	585.29
E3	103.19	2.20	0.65	32.44	616.41	1.62	31.12	30.82	585.29
E4	103.19	2.27	0.98	32.44	616.41	1.62	31.12	30.82	585.29
E5	103.19	2.12	0.99	32.44	616.41	1.62	31.12	30.82	585.29
E6	103.19	2.18	0.99	32.44	616.41	1.62	31.12	30.82	585.29
E7	103.19	2.24	1.33	32.44	616.41	1.62	31.12	30.82	585.29
E8	103.19	2.26	1.35	32.44	616.41	1.62	31.12	30.82	585.29
E9	103.19	2.31	1.34	32.44	616.41	1.62	31.12	30.82	585.29
E10	103.19	2.23	0.66	—					
E11	103.19	2.26	0.66						
E12	103.19	2.27	0.66						
E13	103.19	2.32	0.99						
E14	103.19	2.30	0.99						
E15	103.19	2.29	0.99						
E16	103.19	2.37	1.34						
E17	103.19	2.29	1.35						
E18	103.19	2.36	1.32						

Modelling of life cycle inventory (LCI) was performed using Simapro 8.5 software with the Ecoinvent V1.02 database. For the electrical energy consumption, Sri Lankan (Electricity, low voltage {LK}, market for electricity) data was used. For the water, global (Tap water {GLO} market group for APOS) data set for the tap water was used. However, the workpiece material (AISI P20), cutting insert material (TCMT16T304) and, EcoCool 700 NBF M are not available in the Ecoinvent database. Therefore, those materials were modelled considering their chemical compositions, using 'GLO' data sets.

4.4.3 Life cycle impact assessment

The analyzing method, ReCiPe 2016 Midpoint (H) V1.02 was used to quantify the environmental impact. The ReCiPe 2016 method can focus on a wider range of impact categories compared to other impact assessment methods. Under the damage category of Ecosystem, the ReCiPe 2016 evaluates the damage on terrestrial water, freshwater and marine water. But the Eco-Indicator 99 evaluates the damage on terrestrial water only [134]. The ReCiPe endpoint method focuses burdens on three major areas; Ecosystem, Resources and, Human health. Further, it can be used to express the impact as a unitless figure, Ecopoints, which could be used to compare the impacts of different scenarios easily for laypersons. Furthermore, it can provide large information relevant to the environment compared to the midpoint method. However, the uncertainty of the endpoint method is higher than the midpoint method [135]. However, in this endpoint method, the damage to the man-made environment is not analysed [134].

The environmental impacts under 18 impact categories were evaluated and results are shown in Table 4-3 and Table 4-4. The obtained results were first analysed using Microsoft Excel software considering the contribution of each input on different impact categories. Next, the correlation between environmental impacts and the operating conditions was assessed. Finally, to determine the influence of change of process parameters on the environmental impacts, ANOVA analysis was performed using Minitab 19 statistical software. In here means of impact categories ($\bar{Y}_j$) with respect to the levels of operating conditions were evaluated following Equation 4-4.

$$\bar{Y}_j = \frac{\sum_{i=1}^{n} Y_{ij}}{n} \qquad \text{Equation 4-4}$$

Where, 'Y_{ij}' is the i^{th} response in j^{th} level of cutting parameter and 'n' is the number of responses. Most of the environmental impacts in the considered cooling condition shown an identical behaviour. Hence, impact category, Human toxicity: non-cancer (HTnc) in both wet and dry machining are considered for the discussion.

Table 4-3: Life cycle impacts of turning operations under flood lubrication

Impact category	**Unit**	**Operating Condition**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Climate change (CC)	kg CO_2 eq	1.94E+00	1.95E+00	1.96E+00	2.09E+00	1.98E+00	2.03E+00	2.17E+00	2.19E+00	2.22E+00
Ozone depletion (OD)	kg CFC11 eq	1.26E-06	1.26E-06	1.27E-06	1.33E-06	1.27E-06	1.30E-06	1.36E-06	1.37E-06	1.39E-06
Ionising radiation (IR)	kBq Co-60 eq	3.39E-02	3.39E-02	3.39E-02	4.03E-02	3.95E-02	3.99E-02	4.67E-02	4.71E-02	4.73E-02
Photochemical oxidant formation: Human health (POFH)	kg NO_x eq	7.11E-03	7.12E-03	7.15E-03	7.77E-03	7.40E-03	7.57E-03	8.18E-03	8.26E-03	8.37E-03
Fine particulate matter formation (PMF)	kg PM2.5 eq	4.90E-03	4.90E-03	4.92E-03	5.28E-03	5.03E-03	5.14E-03	5.49E-03	5.54E-03	5.62E-03
Photochemical oxidant formation: Terrestrial ecosystems (POFE)	kg NO_x eq	7.19E-03	7.20E-03	7.22E-03	7.85E-03	7.49E-03	7.65E-03	8.28E-03	8.36E-03	8.47E-03
Terrestrial acidification (TA)	kg SO_2 eq	1.30E-02	1.30E-02	1.30E-02	1.38E-02	1.31E-02	1.34E-02	1.41E-02	1.43E-02	1.45E-02
Freshwater eutrophication (FE)	kg P eq	2.46E-03	2.46E-03	2.46E-03	2.52E-03	2.49E-03	2.50E-03	2.56E-03	2.57E-03	2.58E-03
Marine eutrophication (ME)	kg N eq	7.32E-05	7.33E-05	7.36E-05	7.73E-05	7.52E-05	7.61E-05	7.99E-05	8.03E-05	8.11E-05
Terrestrial ecotoxicity (TET)	kg 1,4-DCB	6.12E+00	6.13E+00	6.15E+00	6.72E+00	6.41E+00	6.55E+00	7.12E+00	7.19E+00	7.28E+00
Freshwater ecotoxicity (FET)	kg 1,4-DCB	4.13E-01	4.13E-01	4.14E-01	4.20E-01	4.15E-01	4.17E-01	4.23E-01	4.24E-01	4.26E-01
Marine ecotoxicity (MET)	kg 1,4-DCB	5.68E-01	5.68E-01	5.69E-01	5.78E-01	5.71E-01	5.74E-01	5.82E-01	5.84E-01	5.86E-01
Human toxicity: cancer (HTc)	kg 1,4-DCB	2.34E-01	2.34E-01	2.34E-01	2.40E-01	2.37E-01	2.38E-01	2.44E-01	2.45E-01	2.46E-01
Human toxicity: non-cancer (HTnc)	kg 1,4-DCB	1.25E+01	1.25E+01	1.25E+01	1.26E+01	1.26E+01	1.26E+01	1.28E+01	1.28E+01	1.28E+01
Land use (LO)	m^2a crop eq	5.39E-02	5.39E-02	5.39E-02	6.91E-02	6.80E-02	6.86E-02	8.45E-02	8.53E-02	8.56E-02
Mineral resource scarcity (MRD)	kg Cu eq	8.53E-02	8.52E-02	8.50E-02	1.11E-01	1.11E-01	1.11E-01	1.38E-01	1.40E-01	1.39E-01
Fossil resource scarcity (FD)	kg oil eq	5.21E-01	5.21E-01	5.24E-01	5.62E-01	5.33E-01	5.45E-01	5.83E-01	5.88E-01	5.97E-01
Water use (WD)	m^3	7.04E-03	7.05E-03	7.07E-03	7.96E-03	7.72E-03	7.83E-03	8.75E-03	8.82E-03	8.89E-03

Table 4-4: Life cycle impacts of turning operations under dry machining

Impact category	**Unit**	**Operating Condition**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Climate change (CC)	kg CO_2 eq	1.96E+00	1.98E+00	1.99E+00	2.11E+00	2.10E+00	2.10E+00	2.25E+00	2.19E+00	2.24E+00
Ozone depletion (OD)	kg CFC11 eq	1.19E-06	1.21E-06	1.21E-06	1.27E-06	1.26E-06	1.26E-06	1.33E-06	1.30E-06	1.33E-06
Ionising radiation (IR)	kBq Co-60 eq	3.31E-02	3.33E-02	3.34E-02	3.97E-02	3.96E-02	3.96E-02	4.67E-02	4.62E-02	4.62E-02
Photochemical oxidant formation: Human health (POFH)	kg NO_x eq	7.18E-03	7.25E-03	7.29E-03	7.85E-03	7.80E-03	7.80E-03	8.48E-03	8.28E-03	8.43E-03
Fine particulate matter formation (PMF)	kg PM2.5 eq	4.95E-03	4.99E-03	5.02E-03	5.34E-03	5.31E-03	5.30E-03	5.69E-03	5.56E-03	5.66E-03
Photochemical oxidant formation: Terrestrial ecosystems (POFE)	kg NO_x eq	7.25E-03	7.32E-03	7.36E-03	7.93E-03	7.88E-03	7.88E-03	8.57E-03	8.37E-03	8.52E-03
Terrestrial acidification (TA)	kg SO_2 eq	1.31E-02	1.33E-02	1.34E-02	1.40E-02	1.39E-02	1.39E-02	1.48E-02	1.43E-02	1.47E-02
Freshwater eutrophication (FE)	kg P eq	2.46E-03	2.47E-03	2.48E-03	2.53E-03	2.53E-03	2.52E-03	2.59E-03	2.57E-03	2.59E-03
Marine eutrophication (ME)	kg N eq	6.73E-05	6.77E-05	6.80E-05	7.14E-05	7.12E-05	7.11E-05	7.53E-05	7.41E-05	7.50E-05
Terrestrial ecotoxicity (TET)	kg 1,4-DCB	6.17E+00	6.22E+00	6.26E+00	6.78E+00	6.74E+00	6.73E+00	7.36E+00	7.19E+00	7.31E+00
Freshwater ecotoxicity (FET)	kg 1,4-DCB	4.14E-01	4.15E-01	4.16E-01	4.21E-01	4.20E-01	4.20E-01	4.27E-01	4.24E-01	4.27E-01
Marine ecotoxicity (MET)	kg 1,4-DCB	5.70E-01	5.71E-01	5.72E-01	5.79E-01	5.79E-01	5.78E-01	5.88E-01	5.84E-01	5.87E-01
Human toxicity: cancer (HTc)	kg 1,4-DCB	2.35E-01	2.35E-01	2.36E-01	2.41E-01	2.41E-01	2.40E-01	2.47E-01	2.45E-01	2.47E-01
Human toxicity: non-cancer (HTnc)	kg 1,4-DCB	1.25E+01	1.25E+01	1.25E+01	1.26E+01	1.26E+01	1.26E+01	1.28E+01	1.28E+01	1.28E+01
Land use (LO)	m^2a crop eq	5.40E-02	5.42E-02	5.43E-02	6.94E-02	6.92E-02	6.93E-02	8.59E-02	8.53E-02	8.48E-02
Mineral resource scarcity (MRD)	kg Cu eq	8.52E-02	8.52E-02	8.51E-02	1.11E-01	1.11E-01	1.11E-01	1.39E-01	1.40E-01	1.38E-01
Fossil resource scarcity (FD)	kg oil eq	5.16E-01	5.21E-01	5.24E-01	5.58E-01	5.54E-01	5.53E-01	5.95E-01	5.79E-01	5.92E-01
Water use (WD)	m^3	6.84E-03	6.89E-03	6.91E-03	7.77E-03	7.74E-03	7.73E-03	8.71E-03	8.58E-03	8.65E-03

4.5 Multi-response optimisation

To identify the best operating condition which minimizes energy consumption (E), surface roughness (Ra), and MWF consumption (MWF_C) and maximizes MRR, Grey-based Taguchi method was used [136]. The multi-response optimisation was performed using the following steps.

Step 1 – S/N ratios of each response were calculated using Minitab 19 statistical software. A “lower the better” condition was applied for E, Ra, and MWF_c and corresponding S/N ratios were obtained from Equation 4-5 while Equation 4-6 used to calculate S/N ratios of MRR which followed a “higher the better” condition. Results are shown in Table 4-5.

$$\eta = S/N = -10log_{10}\left(\frac{\sum_{i=1}^{n} y_i^2}{n}\right) \qquad \text{Equation 4-5}$$

$$\eta = S/N = -10log_{10}\left(\frac{\sum_{i=1}^{n} 1/y_i^2}{n}\right) \qquad \text{Equation 4-6}$$

Step 2 – Normalized S/N ratios Z_{ij}, were calculated by following Equation 4-7 for “lower the better” condition and Equation 4-8 for “higher the better” condition. Results are shown in Table 4-5.

$$Z_{ij} = \frac{\max(\eta_{i=1\ldots9})-\eta_i}{\max(\eta_{i=1\ldots9})-\min(\eta_{i=1\ldots9})} \qquad \text{Equation 4-7}$$

$$Z_{ij} = \frac{\eta_i-\min(\eta_{i=1\ldots9})}{\max(\eta_{i=1\ldots9})-\min(\eta_{i=1\ldots9})} \qquad \text{Equation 4-8}$$

Table 4-5: S/N ratios and normalized S/N ratios of responses (E: energy consumption, Ra: surface roughness, MWF_C: MWF consumption, MRR: Material removal rate)

Ex. No	S/N ratios				Normalized S/N ratios			
	E	**MRR**	**Ra**	**MWF_c**	**E**	**MRR**	**Ra**	**MWF_c**
1	-66.7265	36.3986	-0.5061	-48.2965	0.6348	0.0000	0.9183	0.9999
2	-66.7395	43.8901	-7.3098	-48.3823	0.6174	0.6065	0.3856	0.5619
3	-66.7885	48.7508	-12.2345	-48.4924	0.5521	1.0000	0.0000	0.0000
4	-67.0463	41.7880	0.5374	-48.3505	0.2085	0.4363	1.0000	0.7243
5	-66.4525	47.5684	-6.1070	-48.4599	1.0000	0.9043	0.4798	0.1661
6	-66.7175	42.0350	-10.4749	-48.3539	0.6468	0.4563	0.1378	0.7072
7	-66.9383	45.4737	0.0000	-48.4118	0.3525	0.7347	0.9579	0.4114
8	-67.0251	40.9380	-8.0624	-48.3396	0.2368	0.3675	0.3267	0.7798
9	-67.2027	47.4119	-12.1491	-48.4559	0.0001	0.8916	0.0067	0.1865

Step 3 – Deviation sequences Δ_i, were calculated by following Equation 4-9. Where Z_0 is the reference sequence that equals to 1.

$$\Delta_i = Z_0 - Z_i \qquad \text{Equation 4-9}$$

Step 4 – Grey relation coefficients γ_{ij}, of each response were calculated by using Equation 4-10.

$$\gamma_{ij} = \frac{\Delta_{min} + \varepsilon\Delta_{max}}{\Delta_i + \varepsilon\Delta_{max}} \qquad \text{Equation 4-10}$$

Where, ε is the distinguishing coefficient, defined in the range of $0 \leq \varepsilon \leq 1$, can be changed according to the practical needs and importance of the responses. E is the most important response. Therefore ε for E was taken as 0.75. It was considered other responses, Ra, MWF_c, and MRR, equal in importance and 0.5 was taken as ε [137].

Step 5 – Grey relational grade (GRG) was calculated using Equation 4-11.

$$\overline{\gamma_i} = \frac{1}{k}\sum_{j=1}^{k} \gamma_{ij} \qquad \text{Equation 4-11}$$

Where; k = Total number of responses (4)

i = Operating condition ($i = 1, 2 \ldots\ldots 9$)

j = Responses (E=1, MRR=2, Ra = 3, MWF_c = 4)

Results of Δ_i, γ_{ij} and $\overline{\gamma_i}$ are summarized in Table 4-6. GRG is a representative of all four responses considered. Hence, the multi-response optimisation process has been converted into a single response optimisation problem. Higher the GRG, better the machining performances [136]. To obtain the best level of each operating condition, S/N ratios of GRG under “higher the better” condition were calculated using Minitab 19 statistical software.

Table 4-6: Deviation sequences, grey relation coefficients and grey relational grades of responses (E: energy consumption, Ra: surface roughness, MWF_C: MWF consumption, MRR: Material removal rate)

Ex. No	**Deviation Sequence, Δ_i**				**Grey relation coefficient, γ_{ij}**				**GRG, $\bar{\gamma_i}$**
	E	**MRR**	**Ra**	**MWF_c**	**E**	**MRR**	**Ra**	**MWF_c**	
1	0.3652	1.0000	0.0817	0.0000	0.6725	0.3333	0.8595	1.0000	0.7163
2	0.3826	0.3935	0.6144	0.4381	0.6622	0.5596	0.4487	0.5330	0.5509
3	0.4479	0.0000	1.0000	1.0000	0.6261	1.0000	0.3333	0.3333	0.5732
4	0.7915	0.5637	0.0000	0.2757	0.4865	0.4701	1.0000	0.6446	0.6503
5	0.0000	0.0957	0.5202	0.8339	1.0001	0.8393	0.4901	0.3748	0.6761
6	0.3532	0.5437	0.8622	0.2928	0.6798	0.4791	0.3670	0.6307	0.5392
7	0.6475	0.2653	0.0421	0.5886	0.5367	0.6533	0.9224	0.4593	0.6429
8	0.7632	0.6325	0.6733	0.2202	0.4956	0.4415	0.4261	0.6942	0.5144
9	1.0000	0.1084	0.9933	0.8135	0.4286	0.8218	0.3348	0.3807	0.4915

4.5.1 Confirmation test

To confirm the optimum operating condition, a confirmation test was performed. Then its machining performances were compared with the initial operating conditions. Finally, an environmental performance analysis was conducted using the results of the confirmation test. Inventory analysis and life cycle impact assessment were performed following the same procedures explained in section 4.4.2 and section 4.4.3. Summary of inventory items is tabulated in Table 4-7. Finally, the environmental impacts of the optimized operating condition were compared with the initial operating conditions.

Table 4-7: Summary of inventory items of the confirmation test

Inputs					**Outputs**			
AISI P20 (g)	**Energy (Wh)**	**Cutting insert (g)**	**EcoCool (g)**	**Water (g)**	**Emissions to air**		**Emissions to soil**	**Emissions to water**
					EcoCool (g)	**Water (g)**	**EcoCool (g)**	**Water (g)**
103.19	2162.82	0.68	31.65	601.38	1.58	30.36	30.07	571.02

CHAPTER 5 RESULTS AND DISCUSSION

This chapter explains the results of background study conducted with Sri Lankan die and mould manufacturing (DMM) centres, the experimental study performed in die and mould facilitation centre, University of Moratuwa, environmental performance analysis and the multi-response optimisation.

5.1 Background study

I. Commonly used lathe operations

The Sri Lankan DMM uses many lathe operations such as turning, facing, parting, grooving, boring and thread cutting. But their varying level of usage causes varying contributions to total energy consumption. The results obtained for the usage of different turning operations in case companies are shown in Figure 5-1. According to the results, the lathe operations, turning, facing and boring have been obtained higher percentages for usage in company A. However, the usage of both turning and facing are the highest in other companies, while the usage of boring is less. Therefore it can be concluded that the lathe operations, turning and facing are used most commonly in DMM sector as illustrated in Figure 5-1. Hence both turning and facing lathe operations should be the highest contributors to the cutting energy during lathe machining. Hence, it is significant to identify the energy consumption by both turning and facing operations and quantify the environmental impact by those operations.

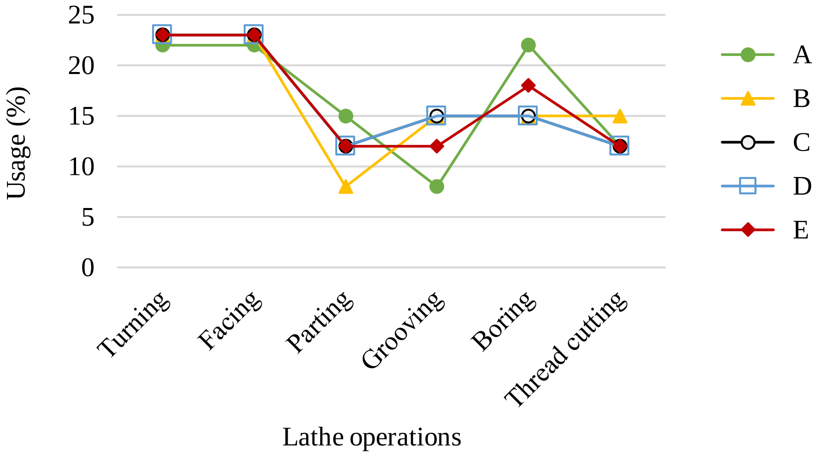

Figure 5-1: Usage of different lathe operations as percentages

II. Commonly used materials

The comparative usage of different materials within each case company is shown in Figure 5-2. All the case companies use two materials, AISI P20 and mild steel. In companies A, B, and E, the material AISI P20 is used mostly. The case companies, C and D largely use EN 19 and mild steel respectively. However, the usage of AISI P20 in company D represents 25% of its total materials usage. Therefore, it is obvious that usage (volume) of AISI P20 compared to other materials is greater. Otherwise, the contribution to environmental impacts due to the usage of AISI P20 during industrial turning process is higher than other materials. Therefore quantifying the environmental impacts during turning of AISI P20 and identifying the strategies to reduce it, leads to enhance the sustainability in the die and mould sector. Therefore, the material AISI P20 will be used to conduct the experiments for LCA of the commercial turning process.

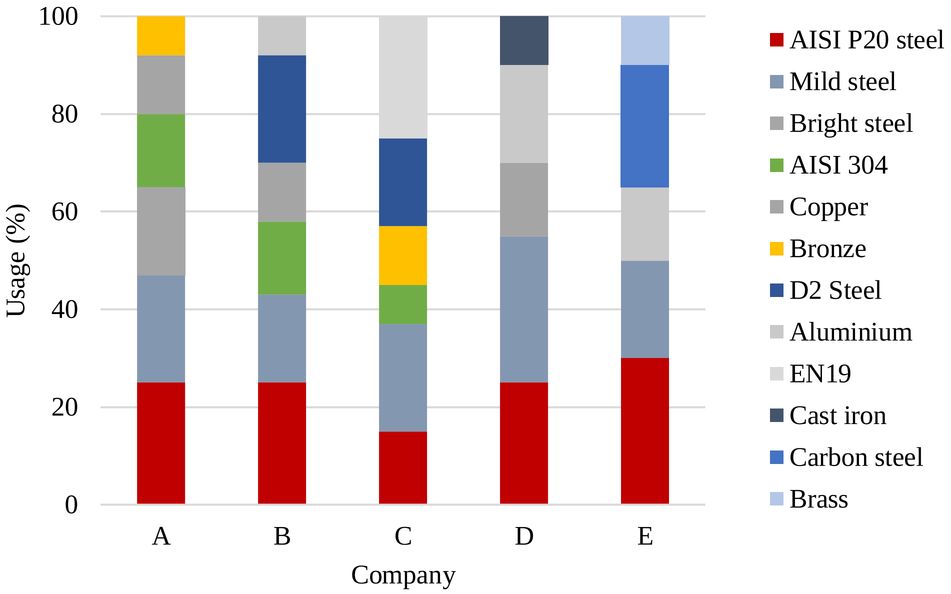

Figure 5-2: Usage of different materials as percentages within case companies

III. Commonly used cooling techniques

The analysed results of the application of those two cooling techniques for the turning of different materials are shown in Figure 5-3. According to that, it is evident that around 90% of materials are machined using wet machining in die and mould manufacturing sector. The flood lubrication system consists of an electric pump. It consumes a significant amount of energy when the lathe machine is powered on. As per literature, the total energy consumption during turning operation is higher when it uses wet machining compared to the dry machining [6].

All the case companies use both wet and dry machining only. The cryogenic lubrication and solid lubrication also can be used to reduce the total cutting energy. Even cryogenic machining demands low energy, the process of liquid Nitrogen (LN_2) production is an energy-intensive one. Therefore the cost of overall machining will be high. Machining with solid lubrication eliminates MWF consumption and leads to the reduction of energy consumption. But it requires a larger amount of energy and cost to produce special tools for this technique [21]. Hence, to reduce energy consumption, introducing new cooling techniques with additional investment is needed. Therefore, obtaining more energy-efficient machining operations using existing facilities leads to increasing the sustainability of machining.

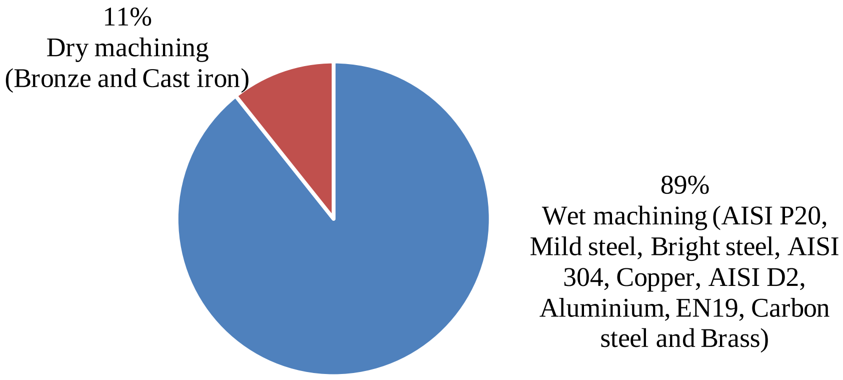

Figure 5-3: Composition of materials machined by wet and dry machining

IV. Machining modes

The lathe machines in die and mould sectors are operated under three modes; ON, OFF and STANDBY. The bar chart in Figure 5-4 represents the machining modes as percentages within a working day in five companies. The percentage, which the machines are operated in ON mode (actual machining period) depends on the workload of each company. But the machining modes during the non-machining period within working hours effect on the total energy consumption. The lathe machines in companies B and E are in OFF mode during the non-machining period, but in companies A, C and D, the machines are operated under STANDBY mode. The percentage of time of standby modes varies between 20%-25%. Therefore, the contribution to the total energy consumption during turning by the non-machining process is nearly a quarter. If companies, A, C and D can reduce the STANDBY time, it leads to a rebate of energy usage, cost of machining and environmental impact [33]. Both companies, B and E are energy efficient than other companies as all the lathe machines are in OFF mode during the non-machining period during working hours. Through the reduction of non-machining time and cutting off the power supply to lathe machines during that period, the energy consumption of turning operation can be reduced.

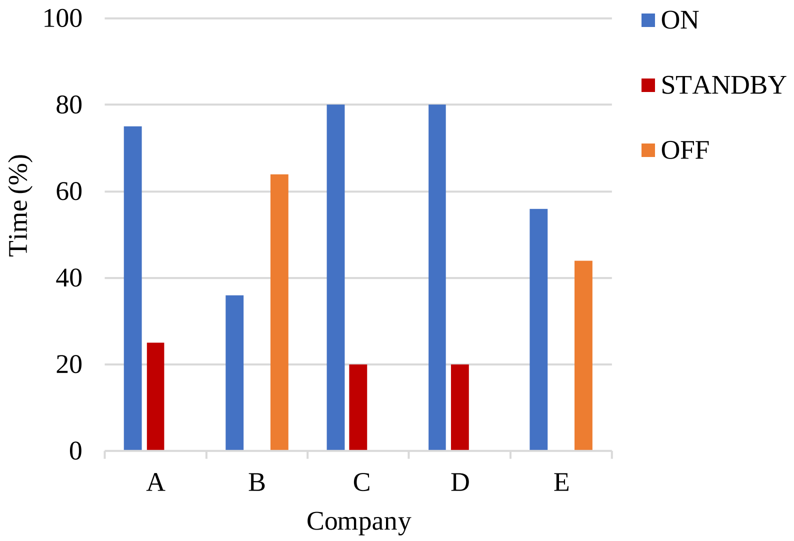

Figure 5-4: Composition of machining modes during a working day

V. Metalworking fluid (MWF) consumption

The usage of MWF during machining is very important to decline the resistance between workpiece and cutting insert, the heat generated at the cutting zone and flush away chips [42]. In flood lubrication, some amount of MWF is wasted during machining. Approximately 5% of MWF by mass is lost with chips, machine tools, handling equipment and as leakages [100] and ultimately ends up in the environment [9]. The consumption of MWF varies with the type of lathe machine and company. The calculated results of MWF consumption in companies except Company D are shown in Table 5-1. The analysed results show that the total amount of MWF which is wasted during turning operation is maximum in Company C and minimum in Company B. Furthermore, the wastage of MWF made by the CNC lathe machines is higher than in manual lathe machines. Therefore, the environmental impact during turning by CNC lathe machines due to usage of MWF is greater. Hence, the necessity to analyse and identify the environmental footprint of CNC lathe machines is essential.

Table 5-1: Wastage of metalworking fluid during turning

		Company						
		A				**B**	**C**	**E**
Type of machine		M[4]	M	M	CNC	M	CNC	M
The volume of MWF tank (l)		20	40	20	125	25	200	30
Topping-up volume of MWF due to evaporation, apportioned per day (l)		0.25	0.5	0.25	1	0.8	3	1.5
Actual machining time per day (Hours)		4.5	4.5	4.5	2.5	4	4	4.75
Amount of MWF consumed per hour (ml)		55	111	55	400	200	750	315.8
Total consumption of MWF (ml) based on machine type	M	221			-	200	-	315.8
	CNC	-			400	-	750	-
Total consumption of MWF (ml) based on company		621				200	750	315.8

5.2 Experimental study

5.2.1 Energy consumption

The correlation between energy consumption and the operating conditions was assessed and the result is shown in Figure 5-5. Energy consumption of dry machining is larger than that of wet machining. Absence of MWF results in larger friction forces between cutting insert and the workpiece and also between the chip and the cutting insert [60]. Larger friction forces lead to larger cutting forces [138]. Greater values of cutting forces result in enlarge the energy consumption during cutting [101].

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[4] M: Manual

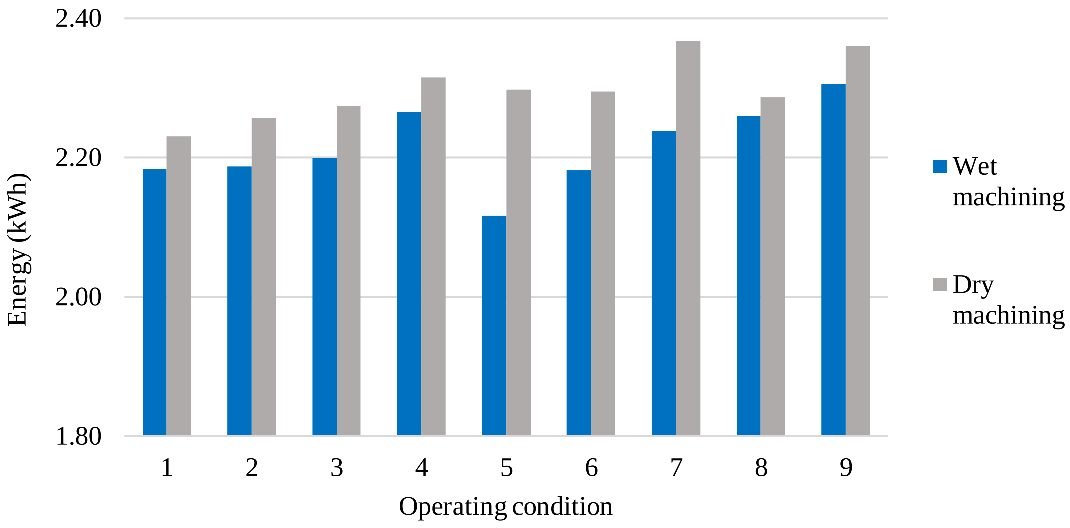

Figure 5-5: Pattern of energy consumption with different operating conditions (Table 3-6)

Portions of energy for different components; machining, non-machining, and overheads are varied with the experiment as illustrated by Figure 5-6. The largest portion of energy was used for overheads in each experiment and its contribution to the total energy consumption is varied between 40% - 44%. Energy consumption for non-machining periods also significant in all experiments. Machining energy component in wet machining is slightly lower (32-38%) than that of dry machining (35-39%).

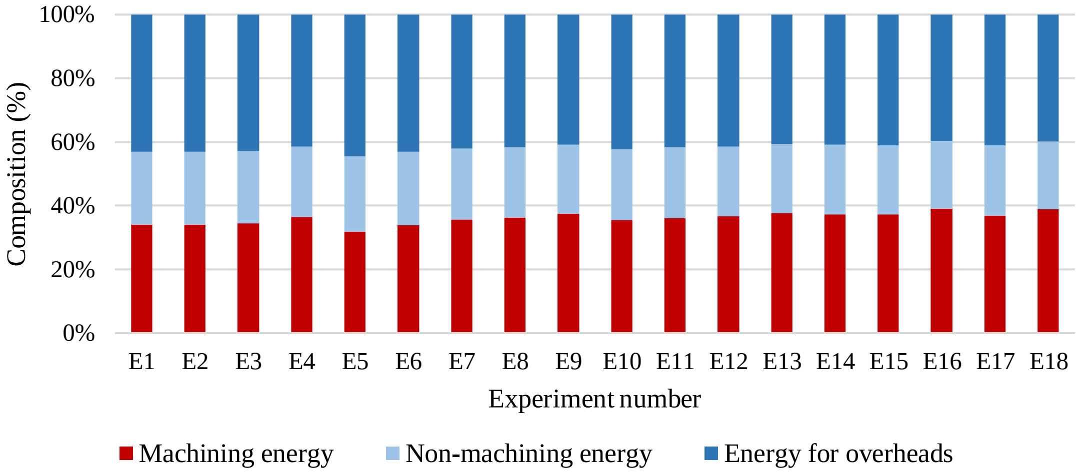

Figure 5-6: Composition of energy consumption during turning each experiment (Table 3-7)

5.2.2 Metalworking fluid consumption

MWF consumption is the top-up volume during turning period. The pattern of MWF consumption during turning operation with different operating conditions was analysed and the result is shown in Figure 5-7. Operating conditions, 3, 5, 7 and 9 in wet machining are responsible for smaller values of MWF usage. Common cutting parameter for operating conditions 3, 5 and 7, is the largest depth of cut (1.65 mm). However, in operating condition 9, both spindle speed and feed rate values are in their largest conditions. Hence, larger depth of cut and the combination of larger spindle speed and feed rate leads to smaller machining time. Smaller machining time results in smaller MWF consumption. Then the top-up volume during turning becomes smaller.

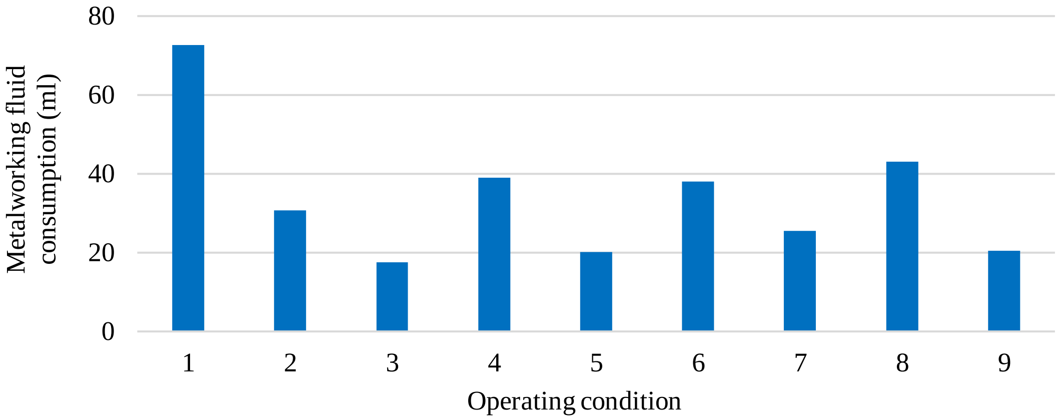

Figure 5-7: Pattern of metalworking fluid consumption with different operating conditions in wet machining (Table 3-6)

5.2.3 Surface roughness (Ra)

The graphical representation of the variation of surface roughness with operating conditions is shown in Figure 5-8. Ra under both machining conditions shows an increasing pattern with rising feed rate. This is also confirmed in the literature [8]. The cutting insert easily moves over the workpiece at low feed rates resulting in better surface finish. At higher feed rates, Ra becomes high due to the appearance of feed marks on the machined surface as mentioned by Risbood et al [139]. Overall, Ra in dry machining is bigger than that in wet machining. Wet machining efficiently controls the temperature at the cutting zone. Smaller cutting temperatures result in lower thermal distortion of the machined region [140]. This causes a low distance between peaks and valleys in surface topography and results in less Ra [141]. However, wet machining fails to absorb heat at the cutting region effectively at high spindle speeds and feed rates, thus resulting in poor surface quality, similar to dry machining.

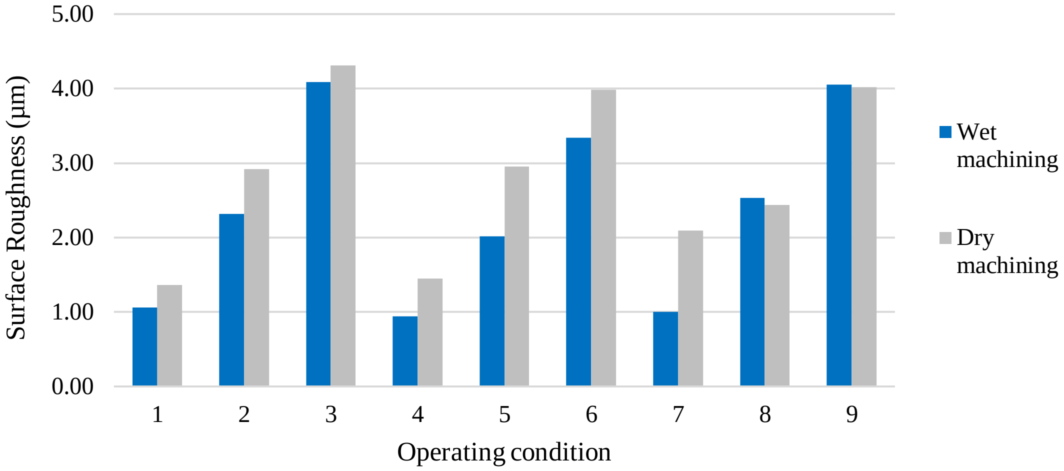

Figure 5-8: Variation of surface roughness with different operating conditions (Table 3-6)

5.2.4 Material removal rate (MRR)

Variation of MRR with operating conditions is illustrated in Figure 5-9. MRR depends on the machining time. Larger the depth of cut (a_p), feed rate (f) and spindle speed (n) the lower the machining time. When the cutting speed is higher, a larger volume of material is evacuated within a small cutting time. When the “f” increases, the feed axis moves fast and the cycle time reduces [6]. Similarly, at higher “a_p”, larger volume of material is abolished during one cut. According to the experimental results of MRR, the highest value of depth of cut (1.65 mm) and combination of the largest feed rate (0.2 mm/rev) and spindle speed (1100 rpm) give smaller machining times. Smaller machining time gives a higher MRR. This result has also been confirmed by Dave et al [142]. MRR of a given operating condition in wet machining is approximately similar to that in dry machining.

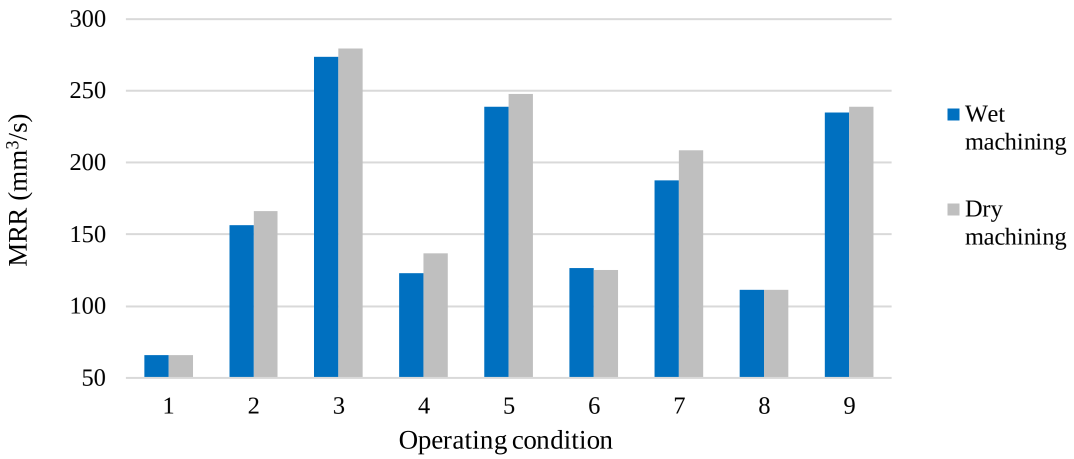

Figure 5-9: Variation of material removal rate with different operating conditions (Table 3-6)

5.3 Environmental performance analysis

To further clarify the effect of key factors of environmental impacts during turning, the first objective of this research (To identify the main factors which affect the environment during turning operation), their contributions on each impact categories were analysed. Figure 5-10 and Figure 5-11 show the contribution (%) of inputs on impact categories during experiments. In the below figures, a consecutive nine bars under an impact category, represent the operating conditions 1 to 9 (Table 3-6). However, to increase the readability at the first vision, only the bars with odd numbers (1, 3, 5, 7, 9) or even numbers (2, 4, 6, 8) were named in the x-axis. According to Figure 5-10 and Figure 5-11, the energy consumption shows the highest contribution among all inputs, on most of the impact categories. The impact categories; climate change (CC) and terrestrial ecotoxicity (TET), and fossil resource scarcity (FD) are influenced by the energy consumption more than 77%, 66% and 75% respectively. Around 52% of electricity is produced from fuel oils (diesel and gasoline) and coal in Sri Lanka [143]. Life cycle impacts of fossil fuel-based energy are significant [144]. Moreover, the workpiece material, AISI P20 also contributes to more than 70% on the impact categories of eutrophication and toxicity.

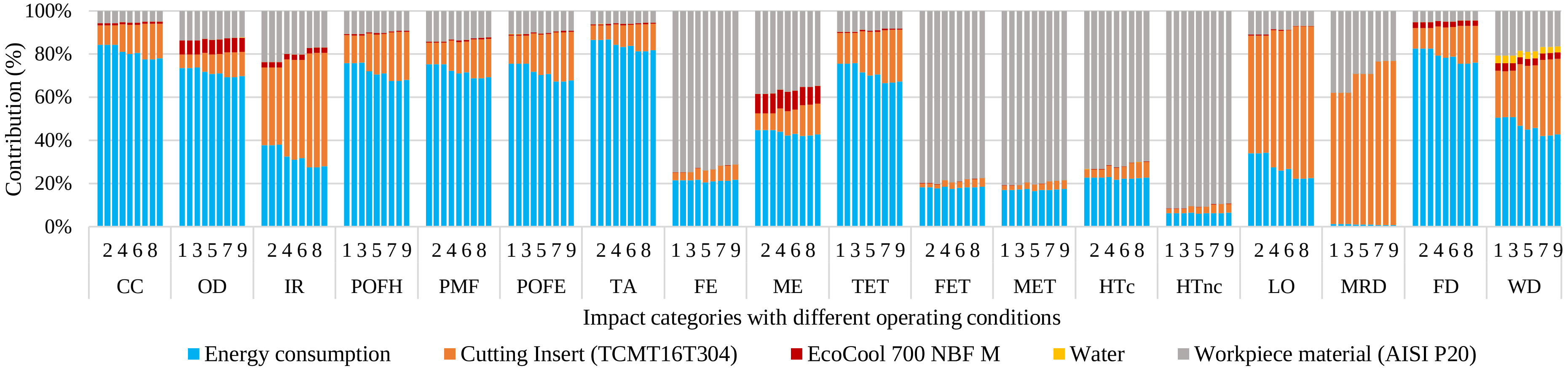

Figure 5-10: Contribution of inputs on impact categories in wet machining under different operating conditions (Table 3-6)

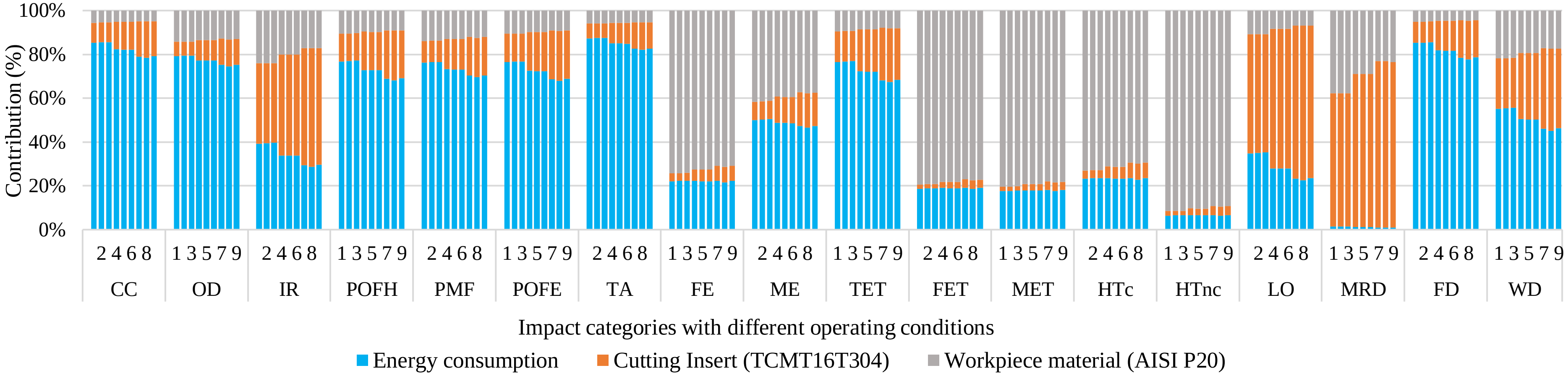

Figure 5-11: Contribution of inputs on impact categories in dry machining under different operating conditions (Table 3-6)

There is an increasing pattern of the contribution of cutting insert material with increasing spindle speed. It largely contributes to the impact categories ionizing radiation (IR), land use (LO) and mineral resource scarcity (MRD) showing more than 35%, 54% and 60% contributions respectively. Due to the larger proportion of metals, Ti and Cr in the workpiece and cutting insert materials, their effects on aquatic ecosystems are higher [145]. However, the effect of MWF on the environment seems negligible.

The base oil of the MWF, EcoCool 700 NBF shows the highest contribution of 9% on marine eutrophication (ME). Its contribution to other impact categories and the effect of water consumption during turning can be neglected. Figure 5-12 illustrates the variation of the contribution of most significant inputs; energy consumption, cutting insert and AISI P20, on climate change (CC), during each experiment. The contribution of cutting insert on CC increases with the increasing spindle speed.

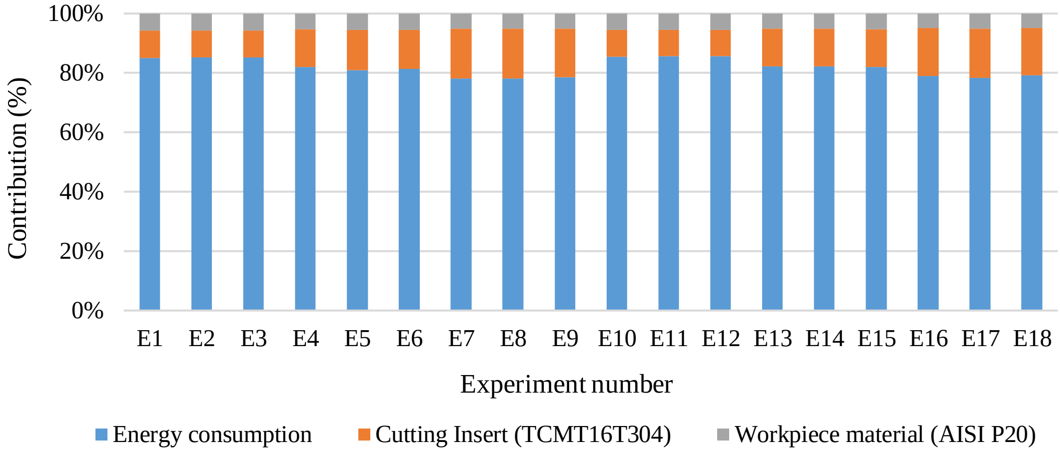

Figure 5-12: Variation of the contribution of energy consumption, cutting insert and workpiece material (AISI P20) on climate change in each experiment (Table 3-7)

To achieve the second objective of the research (To identify the relationship between machining performances and environmental impacts), the variation of environmental impacts with different operating conditions was observed. Most of the impact categories excluding ionizing radiation (IR), land use (LO), mineral resource scarcity (MRD) and water use (WD), show a similar variation with different operating conditions. Hence, the impact category, climate change (CC) with different operating conditions is shown in Figure 5-13 and considered for the discussion. More than 1.94 kg CO_2 eq. was added to the atmosphere due to one hour of turning operation. That equivalent to the impact of burning 0.83 Liters of gasoline [146]. The pattern of variation of CC is similar to the pattern of energy consumption during turning operations under different operating conditions. Moreover, energy is the largest contributor to CC. Hence, it is clear that energy consumption is directly proportional to the CC of a particular turning operation.

However, the impact categories IR, LO, MRD and WD show the increasing impact with the increasing spindle speed (n). This is due to the increasing use of cutting insert material with ‘n’ and a larger effect of cutting insert material on those impact categories. Variation of midpoint impact categories with operating conditions is attached as Appendix C.

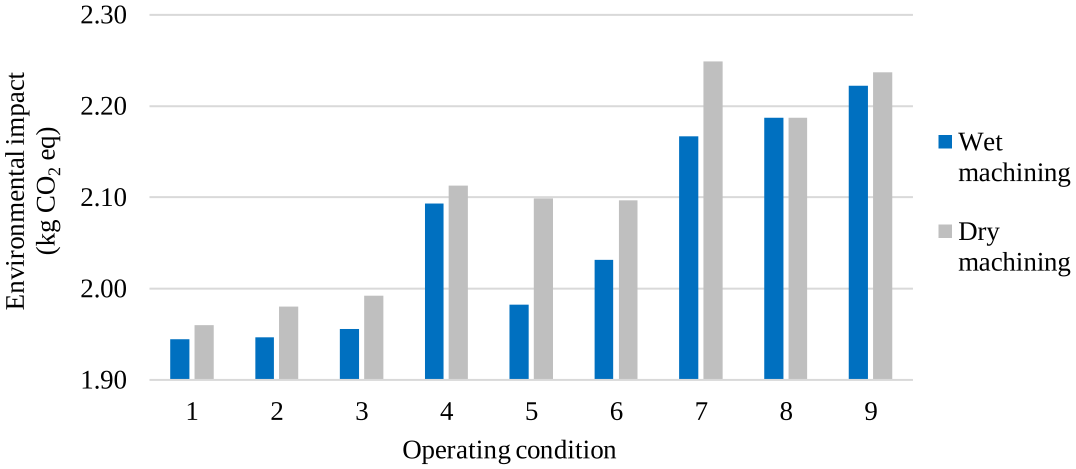

Figure 5-13: Variation of climate change impact with operating conditions (Table 3-6), during one hour of turning

To identify the effect of change of process parameters on the environmental impacts (third objective), means of environmental impacts with respect to the levels of operating conditions were evaluated. Variation of means of Human toxicity: non-cancer (HTnc) in both wet and dry machining is shown in Figure 5-14 and Figure 5-15 respectively. In both wet and dry machining, spindle speed (n) shows a greater effect on the HTPnc than other two cutting parameters; feed rate (f) and depth of cut (a_p). Smaller the ‘n’, smaller the environmental impact. Variation of HTnc with the change of ‘f’ can be neglected. However, HTnc at ‘f’ level 2 is slightly lower than the other two levels in both cooling conditions. Effect of ‘a_p’ on the environmental impact depends on the cooling condition. The smallest HTnc is given by the largest ‘a_p’ in wet machining and the smallest ‘a_p’ in dry machining. However, the effect of ‘a_p’ on the HTnc can be neglected compared to the ‘n’. Similarly, ‘n’ is the highest influencing cutting parameter on the environmental impact while ‘f’ and ‘a_p’ show negligible effects.

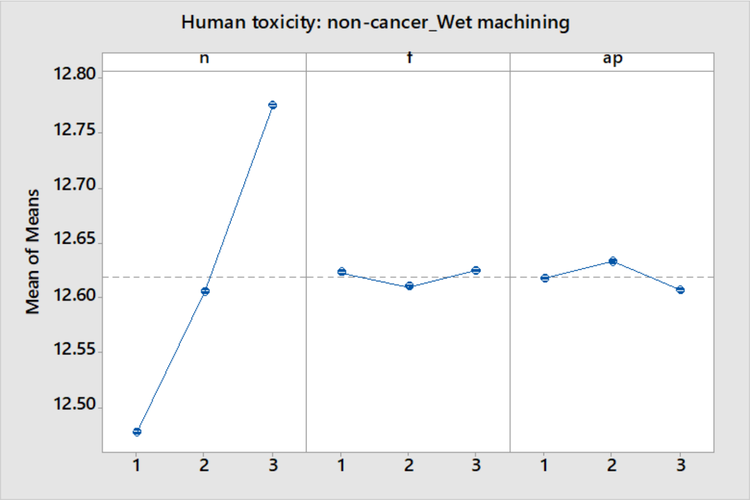

Figure 5-14: Variation of environmental impact with the change of operating conditions in wet machining (n: spindle speed, f: feed rate, a_p: depth of cut)

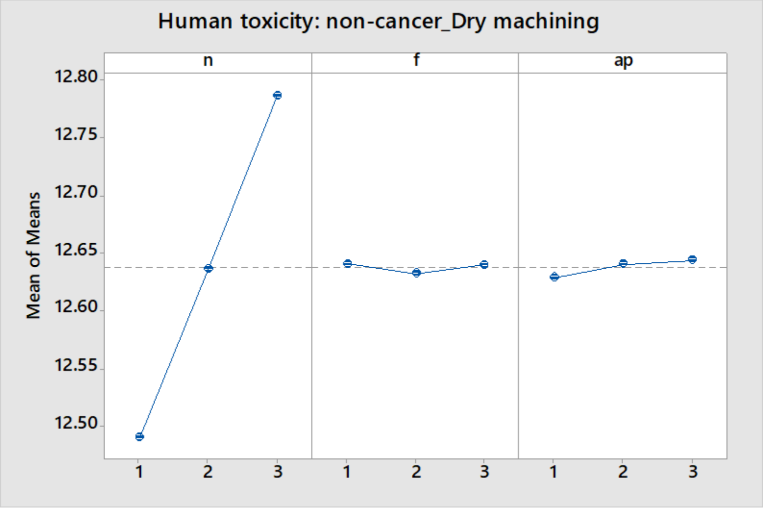

Figure 5-15: Variation of environmental impact with the change of operating conditions in dry machining (n: spindle speed, f: feed rate, a_p: depth of cut)

5.4 Multi-response optimisation

The wet machining shows better environmental performances compared to dry machining. Hence, the machining performances in wet machining were selected for multi-response optimisation. The variation of S/N ratios of grey relational grades (under “higher the better” scenario) with levels of operating conditions is illustrated in Figure 5-16. The level of each cutting parameter corresponds to the highest value of S/N ratio gives the best machining condition. Therefore, level 2 of spindle speed, n (980 rpm), level 1 of feed rate, f (0.10 mm/rev), and level 3 of depth of cut, a_p (1.65 mm) offer the optimum machining performances.

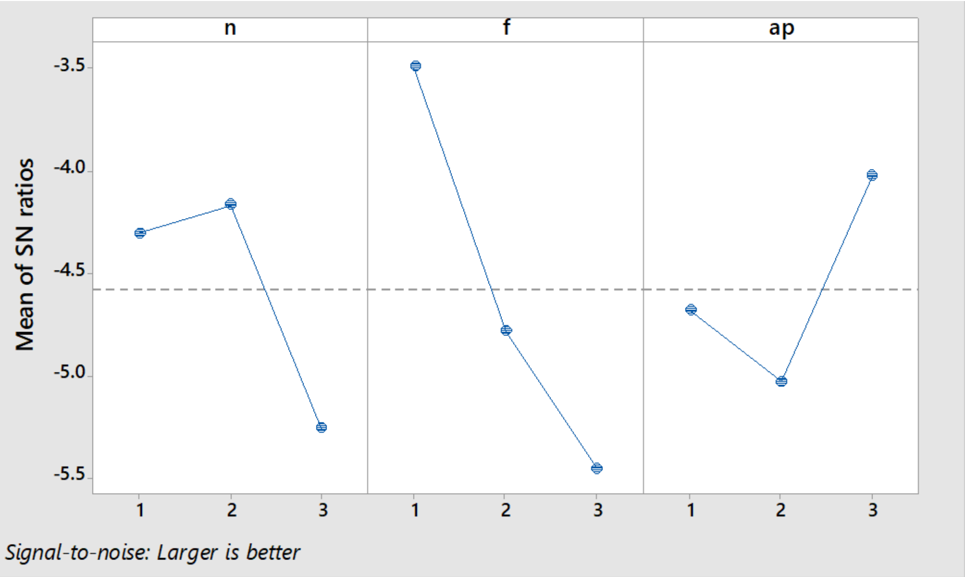

Figure 5-16: Signal to noise ratios of grey relational grades (n: spindle speed, f: feed rate, a_p: depth of cut)

5.4.1 Confirmation test

The results of the confirmation test (CT) are summarized in Table 5-2. The most important response, energy consumption (E) of the CT is 2.16 kWh. Compared to the initial operating conditions, it is relatively smaller as illustrated in Figure 5-17. Ra of CT is smaller than all Ra values in initial operating conditions. MWF consumption (MWF_c) during CT is also relatively smaller. However, the result of the MRR is not at its maximum level as expected. To minimize E, Ra and MWF_c, the MRR has to be slightly compromised.

Table 5-2: Machining performances of the confirmation test

Machining performances	**Result**
Energy consumption	2.17 kWh
Material removal rate	158.38 mm^3/s
Surface roughness	0.52 µm
Metalworking fluid consumed	28.55 ml

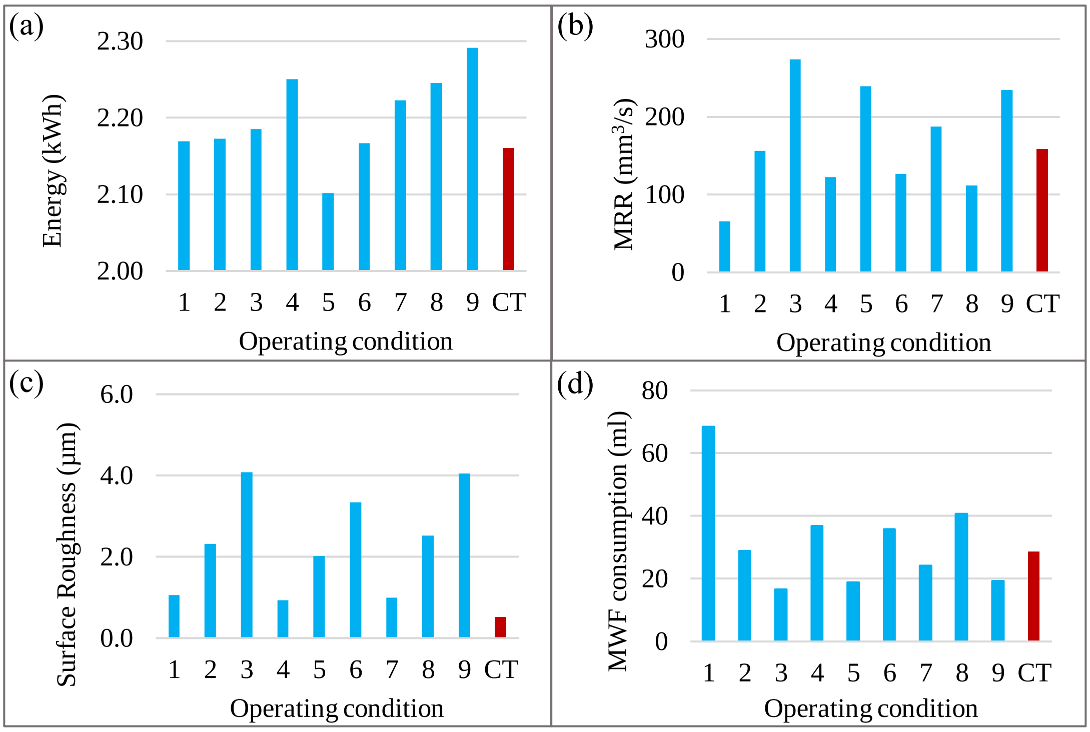

Figure 5-17: Comparison of machining performances of the confirmation test (CT); (a) Energy consumption, (b) Material removal rate (MRR), (c) Surface roughness, and (d) Metalworking fluid consumption

To achieve the final objective of the research (To analyse and compare the environmental impacts of industrial turning operation with the optimized operation), the environmental impacts of the CT were compared with the initial operating conditions and results are shown in Table 5-3. The improvements of environmental impacts with relative to the maximum and minimum values of each impact category in initial operating conditions were evaluated and results are shown in 6th and 7th columns in Table 5-3. When considering the improvements in impact categories of the CT compared to the maximum impact values of initial operating conditions, they vary between 2% – 38%. A larger reduction of environmental impacts was shown by the CT under the impact categories; mineral resource scarcity (MRD) (38%), land use (LO) (36%) and ionizing radiation (IR) (28%). The highest impact categories; human toxicity: non-cancer, terrestrial ecotoxicity and climate change, show 2%, 16% and 12% reduction respectively. Most of the impact categories of CT maintain their values at the minimum level as initial operating conditions. However, there is a slight increment of impact categories; MRD (2%), LO (1%) and IR (1%) compared to their minimum levels. Hence it is clear that the optimized operating condition can be used to obtain better machining and environmental performances.

Table 5-3: Environmental impacts of turning with optimised operation condition

Impact category	**Unit**	**Confirmation test results**	**Results of initial experiments**		**Improvement**	
			Maximum	**Minimum**	**W.r.t.[5] Maximum**	**W.r.t. Minimum**
Climate change	kg CO_2 eq	1.94E+00	2.22E+00	1.94E+00	12%	0%
Ozone depletion	kg CFC11 eq	1.26E-06	1.39E-06	1.26E-06	10%	0%
Ionizing radiation	kBq Co-60 eq	3.41E-02	4.73E-02	3.39E-02	28%	-1%
Photochemical oxidant formation: Human health	kg NO_x eq	7.12E-03	8.37E-03	7.11E-03	15%	0%
Fine particulate matter formation	kg PM2.5 eq	4.90E-03	5.62E-03	4.90E-03	13%	0%
Photochemical oxidant formation: Terrestrial ecosystems	kg NO_x eq	7.20E-03	8.47E-03	7.19E-03	15%	0%
Terrestrial acidification	kg SO_2 eq	1.30E-02	1.45E-02	1.30E-02	11%	0%
Freshwater eutrophication	kg P eq	2.46E-03	2.58E-03	2.46E-03	5%	0%
Marine eutrophication	kg N eq	7.33E-05	8.11E-05	7.32E-05	10%	0%
Terrestrial ecotoxicity	kg 1,4-DCB	6.13E+00	7.28E+00	6.12E+00	16%	0%
Freshwater ecotoxicity	kg 1,4-DCB	4.13E-01	4.26E-01	4.13E-01	3%	0%
Marine ecotoxicity	kg 1,4-DCB	5.68E-01	5.86E-01	5.68E-01	3%	0%
Human toxicity: cancer	kg 1,4-DCB	2.34E-01	2.46E-01	2.34E-01	5%	0%
Human toxicity: non-cancer	kg 1,4-DCB	1.25E+01	1.28E+01	1.25E+01	2%	0%
Land use	m^2a crop eq	5.46E-02	8.56E-02	5.39E-02	36%	-1%
Mineral resource scarcity	kg Cu eq	8.66E-02	1.40E-01	8.50E-02	38%	-2%
Fossil resource scarcity	kg oil eq	5.21E-01	5.97E-01	5.21E-01	13%	0%
Water use	m^3	7.07E-03	8.89E-03	7.04E-03	20%	0%

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[5] With respect to

CHAPTER 6 CONCLUSION

This chapter initially presents the research summary. Then it describes contributions to knowledge and practice based on the literature review, experimental results and environmental performance analysis. Thirdly, the limitations of the research are discussed. Finally, it describes further research areas can be performed based on this research.

6.1 Research summary

This study was designed with the aim of identifying and analysing the life cycle environmental impacts of the commercial turning operation for the target audience of Sri Lankan die and mould manufacturing sector. To achieve this aim, four objectives were defined. The research gap was identified through a detailed literature review focusing sustainability studies of machining operations.

The experimental method was selected as the data collection method. To select the most commonly used workpiece material, machining condition and cutting parameters, for the experiments, a background study was conducted within Sri Lankan die and mould manufacturing sector. Turning operation with dry and wet machining conditions were conducted under a set of different operating conditions given by the Taguchi method (Table 3-6 and Table 3-7). Machining performances in each experiment were recorded (Table 4-1) and analysed. Using life cycle assessment technique, an environmental impact analysis was done using SimaPro 8.5 software with the Ecoinvent database. The analyzing method, ReCiPe 2016 Midpoint (H) V1.02 was used to quantify the environmental impact. The turning with wet machining under given operating conditions were shown better machining performances and less environmental impacts compared to the dry machining. Therefore, multi-response optimisation was carried out using machining performances data of turning with wet machining, to propose a better operating condition. A confirmation test was also conducted to confirm the results of multi-response optimisation.

6.2 Contribution to knowledge and practice

The contributions from this study can be addressed according to the set of objectives. The first objective of identifying the main factors, which affect the environment during turning operation is achieved through the comprehensive literature review. It is evident from the literature that energy and metalworking (MWF) consumption are the key sources of environmental impacts during turning. The literature review was further extended to identify the strategies to reduced use of energy and MWF during turning operation.

The second objective of the research was to identify the relationship between machining performances and environmental impacts. The machining performances of the commercial turning operation were assessed to achieve the first part of the third objective. Energy consumption during turning of AISI P20 with wet machining is less than that of dry machining. In flood lubrication, machining energy varies between 32-38%, while it for dry machining is 35-39%. Non-machining energy during experiments varies from 21% to 24%. Overheads (lights and AC) are responsible for the largest energy components in each experiment and which fluctuates between 40-44%. Overall, around 60% of total energy is consumed for non-productive operations. Reducing operator waiting periods and switching OFF the lathe machine during non-machining periods could lead to decrease the non-machining energy. Energy for overheads could also be reduced by effective and conscious use of the lights and AC units during the non-working period. Larger depth of cut and spindle speed-feed rate combinations result in smaller machining times. It leads to a small amount of MWF usage during the cutting period. Furthermore, smaller machining time results in higher MRRs. Wet machining yields better surface finishes than dry machining as observed with low arithmetical mean surface roughness (Ra). There is an increasing correlation of Ra with the increasing feed rate.

The second part of the second objective is well achieved through the analysis of the environmental performance of turning operation. Environmental impacts of given commercial turning operations are significant and they add over 1.94 kg CO_2 eq. per hour to the atmosphere. The correlation between machining performances and environmental impacts were evaluated. Energy consumption and most of the impact categories were shown similar behavior since energy is the largest contributor to environmental impacts. Which shows more than 65% contribution to most of the impact categories. The cutting insert and workpiece materials also contribute significantly, especially in the freshwater and marine ecosystems categories. However, the effect of MWF on environmental impacts can be neglected, compared to other inputs.

The effect of change of process parameters on the environmental impact was identified as the third objective with an ANOVA analysis. The impact categories are highly influenced by the change of spindle speed (n). The smaller the ‘n’, the smaller the impact. However, the effect of change of both feed rate and depth of cut on environmental impacts can be neglected.

The final objective; to analyse and compare the environmental impact of industrial turning operation with the optimized operation, was achieved through the multi-response optimisation. To obtain the optimum machining performances while keeping the environmental impacts at their minimum level, the best operating condition of: Spindle speed, n = 980 rpm, feed rate, f = 0.10 mm/rev, depth of cut, a_p = 1.65 mm) can be proposed in the given context for turning of AISI P20 under wet machining. Therefore, this study gives good insights to practice sustainable machining in the die and mould manufacturing centres with existing facilities.

Finally, it can be concluded that the study has successfully achieved all defined set of objectives. Therefore, the aim of the research, to identify and analyse the life cycle environmental impacts of the commercial turning operation, has been achieved.

6.3 Research limitations

The research was conducted under several limitations as described below.

- For the background study, the questionnaire was conducted with only five die and mould manufacturers. Out of many die and mould manufacturing facilities located across the country, five independent centres were selected within the close proximity considering research cost and availability of access permission.
- Due to the lack of workpiece material and tool material, each experiment was performed only one time. Therefore, the readings of surface roughness, energy consumption, MWF consumption and material removal rate were taken from a single experiment for the considered operating condition.

- The experimental analysis could have been extended considering different cooling/lubrication methods. However, availability of resources has limited experimental analysis only for two cooling methods. Further, life cycle assessments of other cooling methods were not performed, due to the unavailability of reliable data of them for the life cycle inventory analysis.
- The working period in the machining centre was limited due to COVID- 19. Hence, to collect the energy consumption data the power logger was coupled to the air conditioning system only within two consecutive working days around five hours per each day. Moreover, energy consumption during the non-machining period was obtained from power logger data of three working days when the experiments conducted. Therefore the accuracy of energy data is less.
- The ecoinvent database in SimaPro software doesn't consist the inventory of workpiece material AISI P20, cutting insert material and MWF (EcoCool 700 NBF M). Therefore, those materials were modelled by considering their chemical compositions. However, due to the unavailability of some base materials, materials with approximately similar properties were used during modelling. Lack of accuracy of materials modelling during inventory analysis may cause the uncertainty of impact categories.
- The experiments were conducted in Sri Lanka. However, due to the unavailability of Sri Lankan data in the Ecoinvent database for some inventory items, global data sets were used during modelling of the life cycle inventory of workpiece material, cutting insert material and MWF (EcoCool 700 NBF M and water). If another set of data has been used, the results of the environmental performance analysis could have been different.

6.4 Further research directions

This research was conducted to analyse the environmental impact of commercial turning operation in the Sri Lankan die and mould manufacturing (DMM) sector. Followings are possible further research directions based on this study.

- Further research can be conducted to analyse and optimise the economic aspects of turning in DMM sector.

- The energy study for the environmental performance analysis of this research was limited due to COVID-19. A detail energy study can be performed to enhance the quality of results.
- Gaseous emissions which were excluded from the study could be captured using appropriate equipment and integrating them into the life cycle inventory may yield more accurate LCA results.
- Further research can be performed by extending the LCA considering different materials and cooling/lubrication methods associated with turning operation.

PUBLICATIONS

1. W. L. R. Fernando, H. P. Karunathilake, J. R. Gamage, “Strategies to reduce energy and metalworking fluid consumption for the sustainability of turning operation: A review", *Journal of Cleaner Engineering and Technology* - Reviewer comments addressed.

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APPENDIX A: QUESTIONNAIRE FOR LATHE MACHINE OPERATORS

1. Company Name : ……………………………………………………
2. Details of the lathe machine
   - i. Machine type : Manual ☐ CNC ☐
   - ii. Power consumption (kW) :
3. Details of the machine operating time and actual machining time
   - i. Number of working hours per day :
   - ii. Number machine operating time per day :
   - iii. Average machining hours per day :
   - iv. Mode of machine (On / Off / Standby (ST))

		On	Off	ST
a.	At non-machining periods within working hours :	☐	☐	☐
b.	At non-working period on a working day (Night) :	☐	☐	☐
c.	During holidays :	☐	☐	☐

4. Details about the most commonly used turning methods. Give the ranks based on the usage.
   (1-Rarely used, 4- Most commonly used)

Turning Method	Turning	Facing	Parting	Grooving	Thread turning
Rank					

Question number 5, 6 and 7 are based on the flood lubrication.

5. Details about Lubricating/Coolant pump
   - i. Volume of pump :
   - ii. Power (kW) :
   - iii. Flow rate of MWF can be supplied :
6. Details about used MWF disposing
   - i. Disposal volume (Average) :
   - ii. How often :
   - iii. Please mention if any preprocess is done before the disposing :
7. Details about MWF refilling
   - i. Average volume of refilling MWF
     - a. After disposing process :
     - b. Due to evaporation while machining :
       - How often:

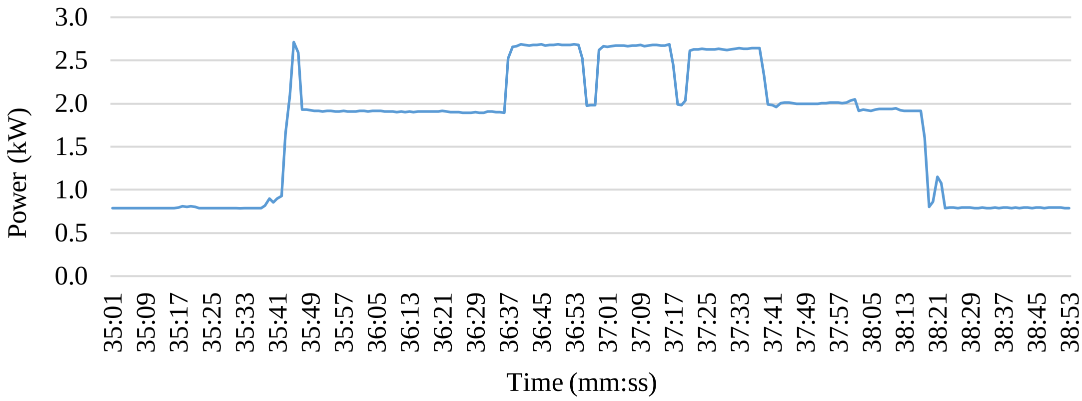
8. Details about the most commonly used materials and cutting conditions. (Cooling techniques: Dry machining, Wet machining, Minimum Quantity Lubrication, Cryogenic or any other)

Material	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)	Tool Insert			Metalworking fluid	Cooling technique
				Type of tool	Tool material	Model number		
1.								
2.								
3.								
4.								
5.								
6.								

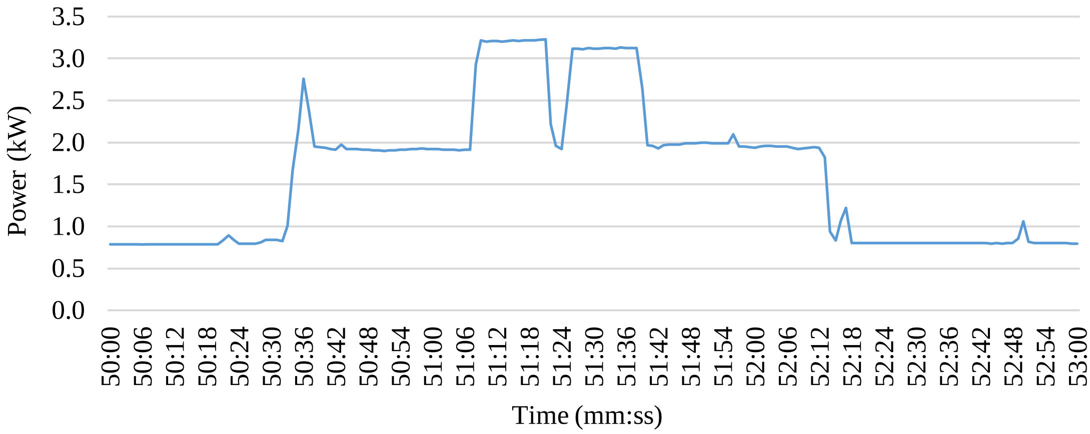
9. Please mention details about any other lubrication method use in your workshop

APPENDIX B: PATTERNS OF POWER CONSUMPTION DURING TURNING OPERATIONS

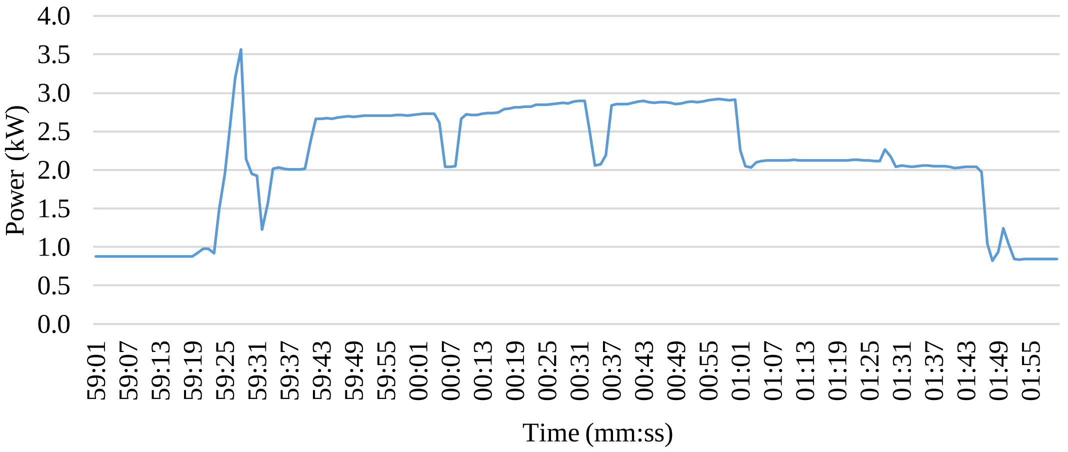
Experiment number 02 (wet machining, n = 860 rpm, f = 0.15 mm/rev, a_p = 1.10 mm)



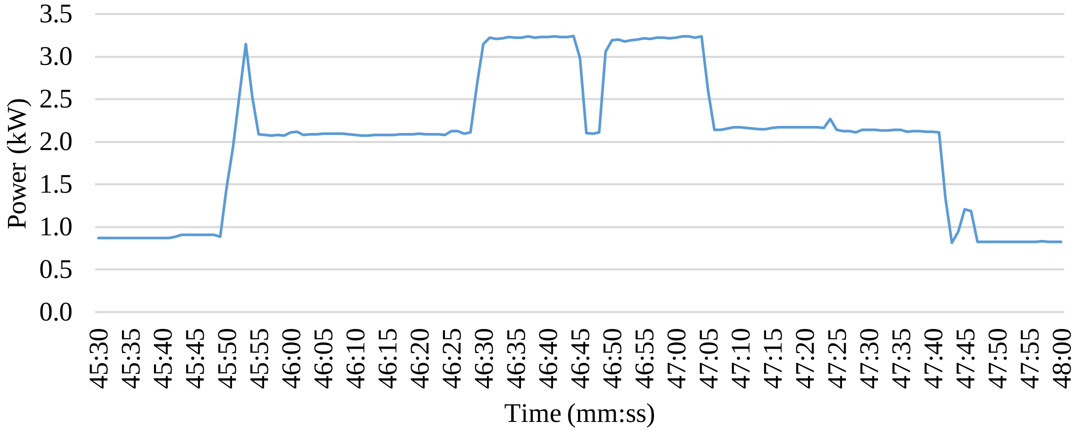
Experiment number 03 (wet machining, n = 860 rpm, f = 0.20 mm/rev, a_p = 1.65 mm)



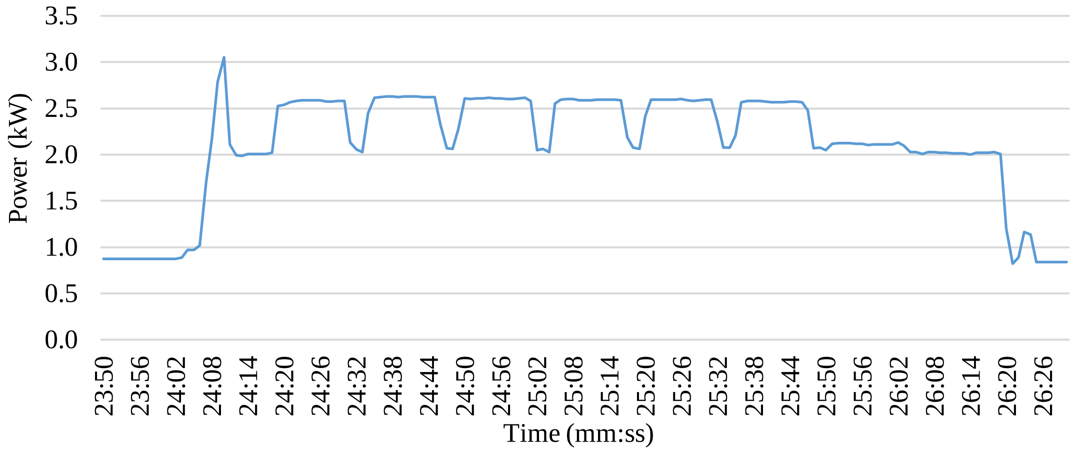
Experiment number 04 (wet machining, n = 980 rpm, f = 0.10 mm/rev, a_p = 1.10 mm)



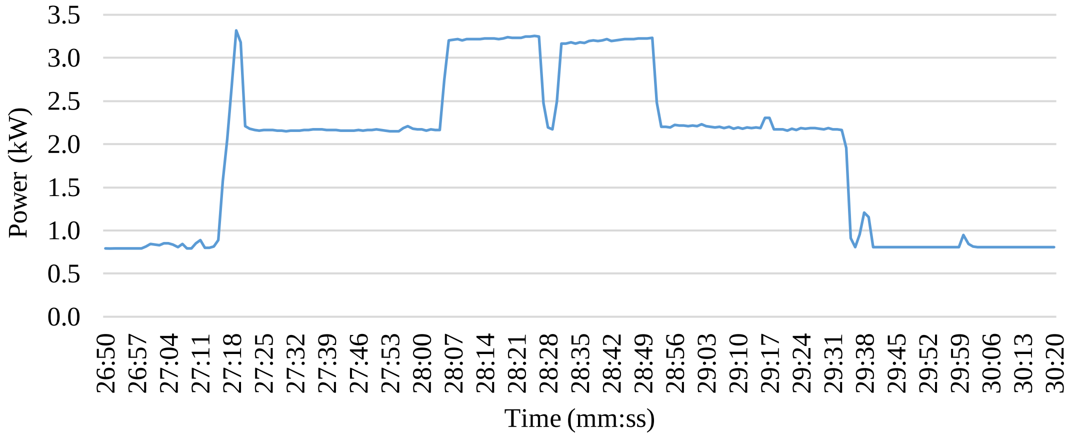
Experiment number 05 (wet machining, n = 980 rpm, f = 0.15 mm/rev, a_p = 1.65 mm)



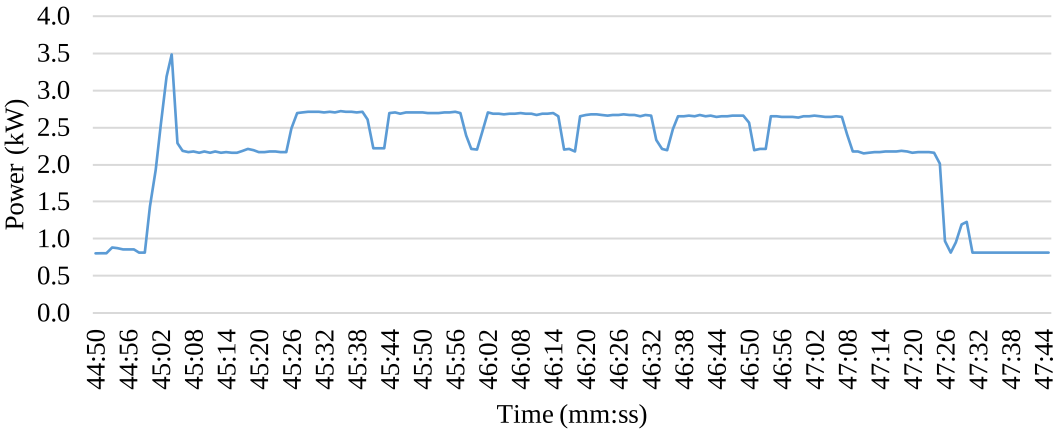
Experiment number 06 (wet machining, n = 980 rpm, f = 0.20 mm/rev, a_p = 0.55 mm)



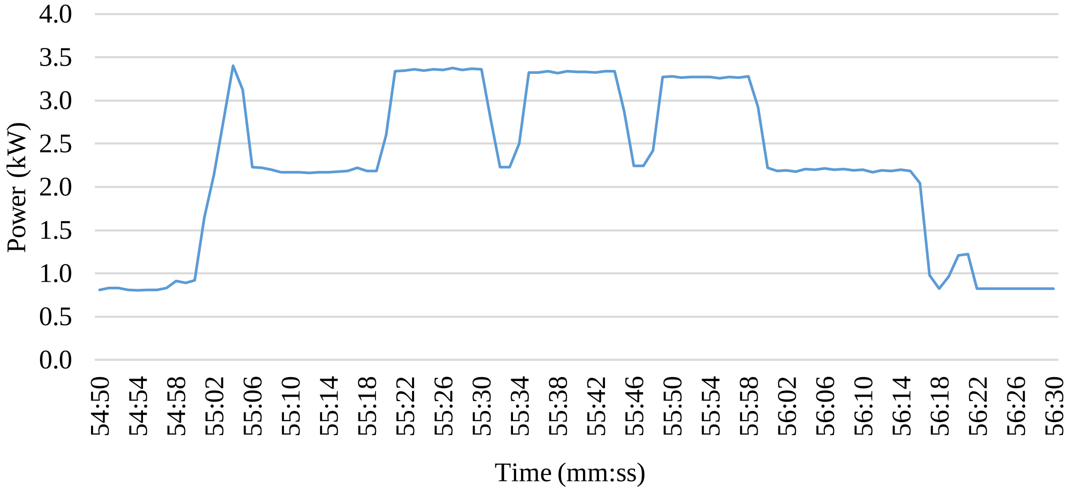
Experiment number 07 (wet machining, n = 1100 rpm, f = 0.10 mm/rev, a_p = 1.65 mm)



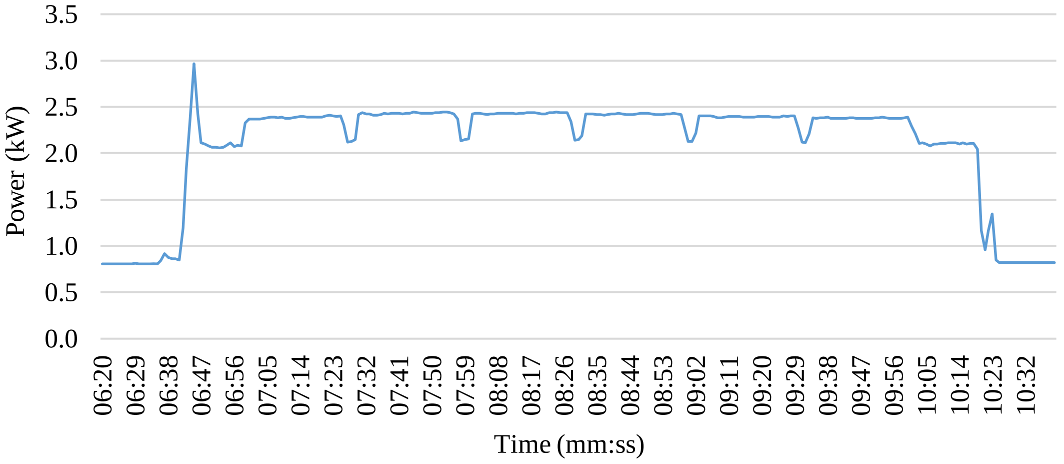
Experiment number 08 (wet machining, n = 1100 rpm, f = 0.15 mm/rev, a_p = 0.55 mm)



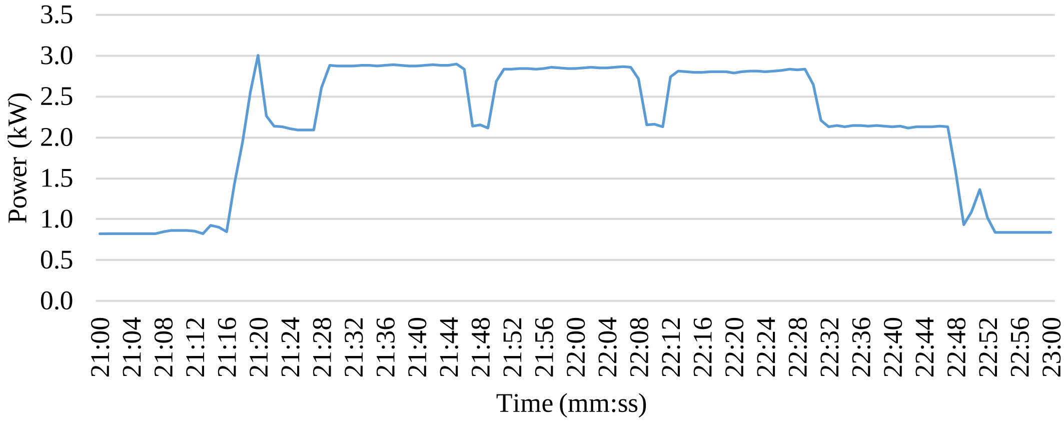
Experiment number 09 (wet machining, n = 1100 rpm, f = 0.20 mm/rev, a_p = 1.10 mm)



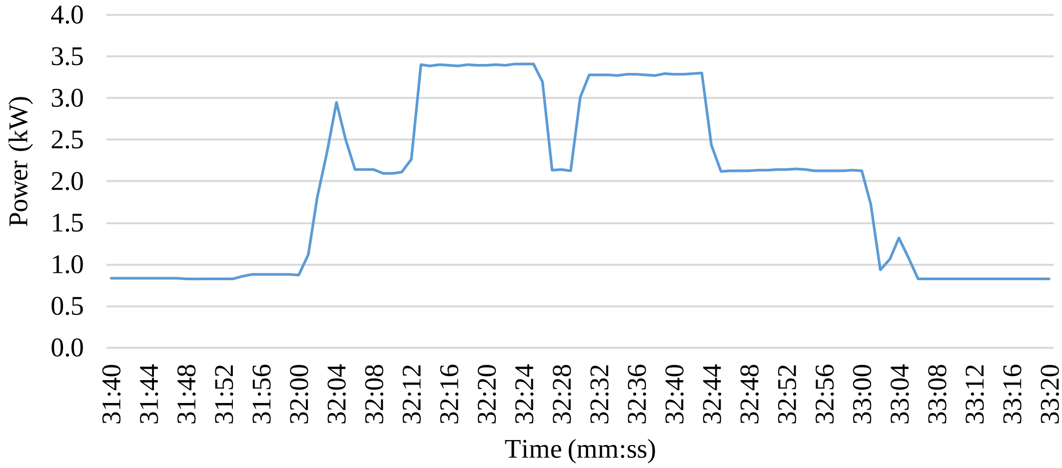
Experiment number 10 (dry machining, n = 860 rpm, f = 0.10 mm/rev, a_p = 0.55 mm)



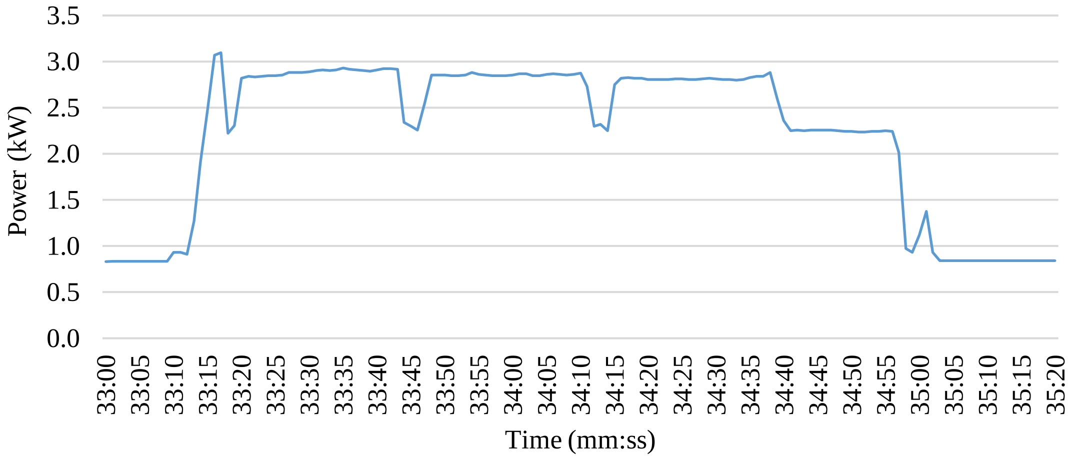
Experiment number 11 (dry machining, n = 860 rpm, f = 0.15 mm/rev, a_p = 1.10 mm)



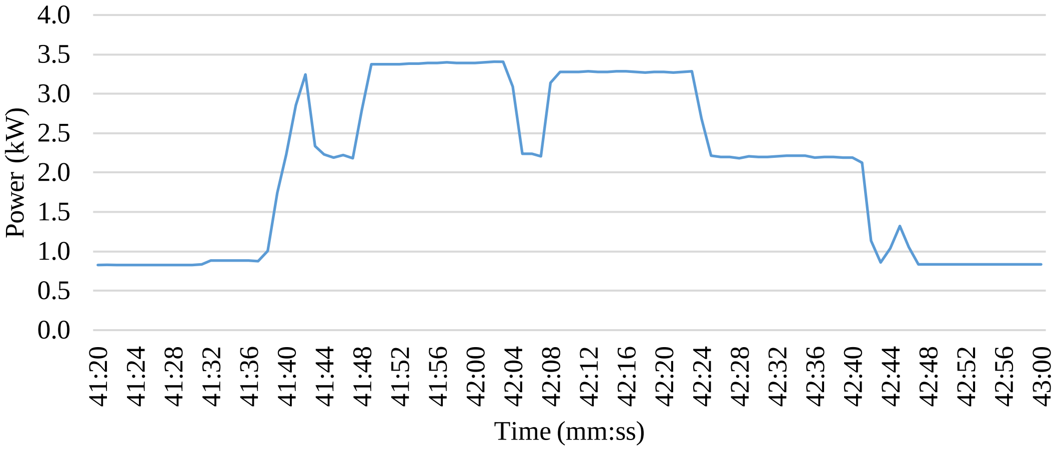
Experiment number 12 (dry machining, n = 860 rpm, f = 0.20 mm/rev, a_p = 1.65 mm)



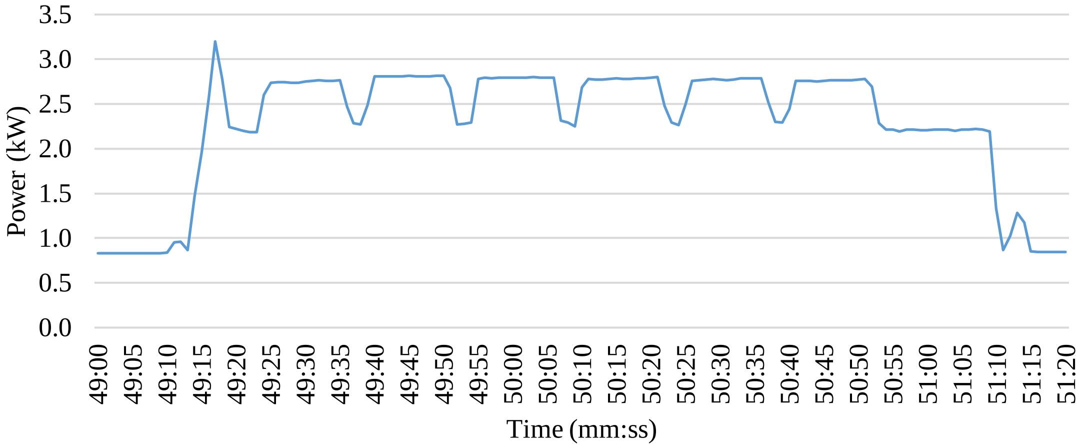
Experiment number 13 (dry machining, n = 980 rpm, f = 0.10 mm/rev, a_p = 1.10 mm)



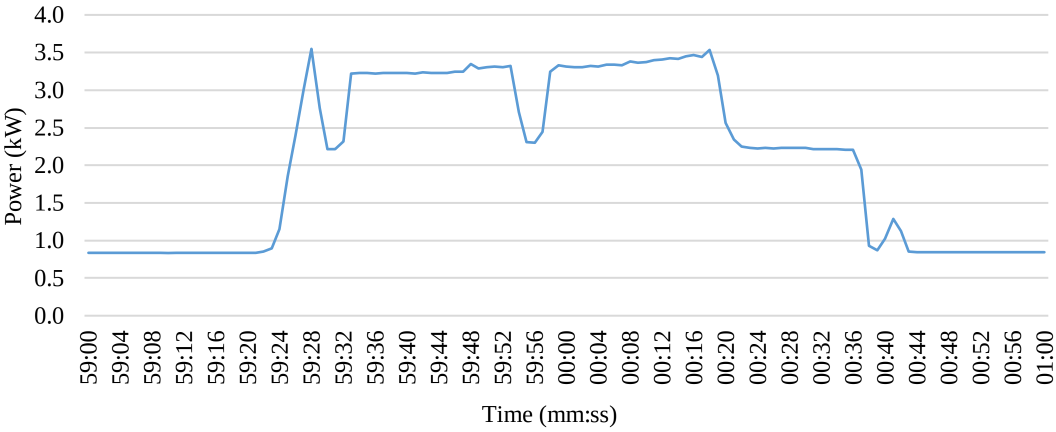
Experiment number 14 (dry machining, n = 980 rpm, f = 0.15 mm/rev, a_p = 1.65 mm)



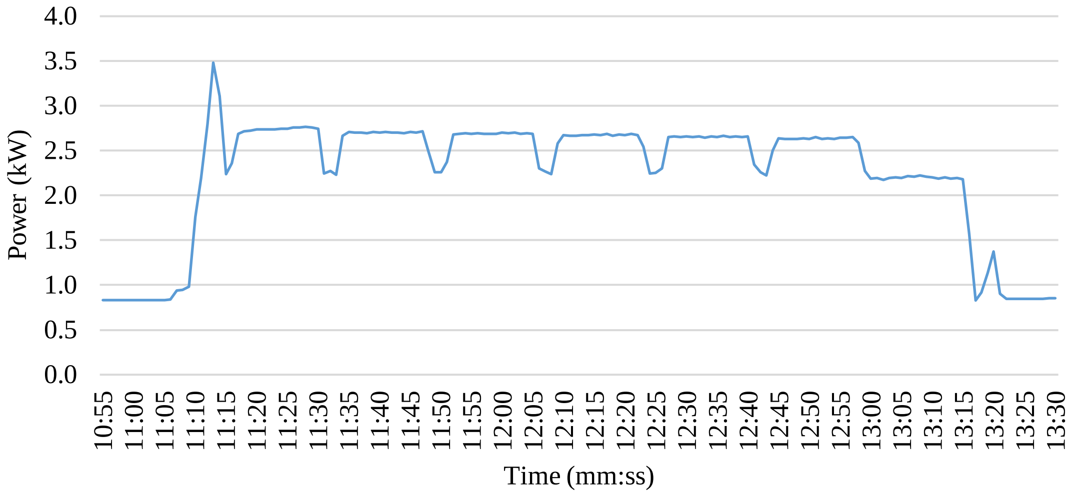
Experiment number 15 (dry machining, n = 980 rpm, f = 0.20 mm/rev, a_p = 0.55 mm)



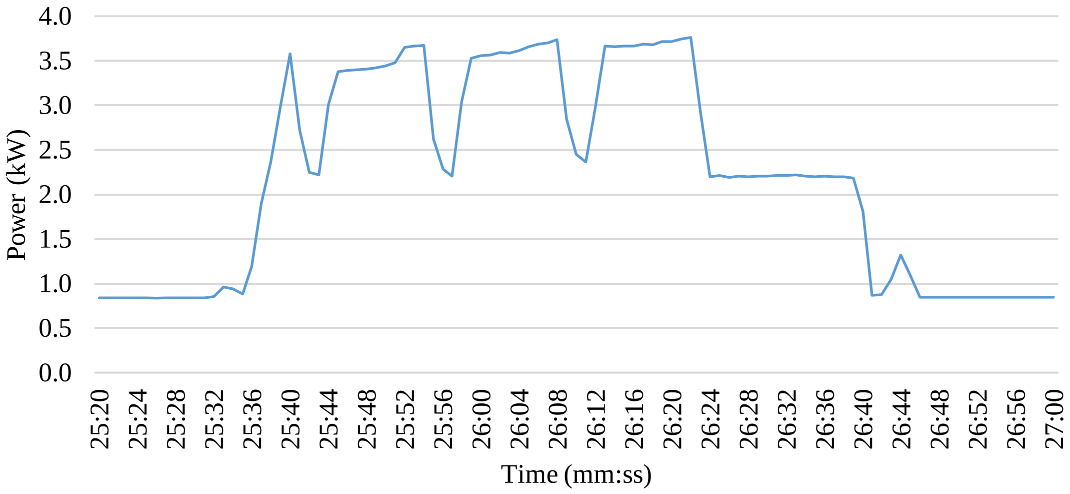
Experiment number 16 (dry machining, n = 1100 rpm, f = 0.10 mm/rev, a_p = 1.65 mm)



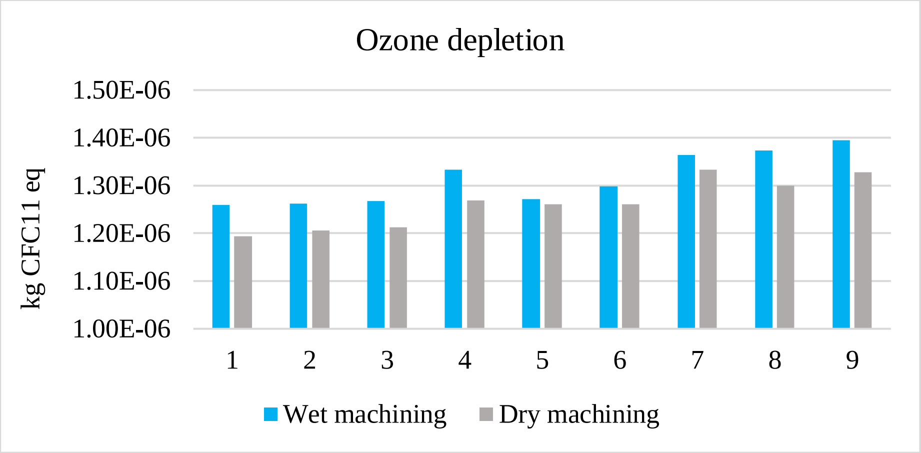
Experiment number 17 (dry machining, n = 1100 rpm, f = 0.15 mm/rev, a_p = 0.55 mm)

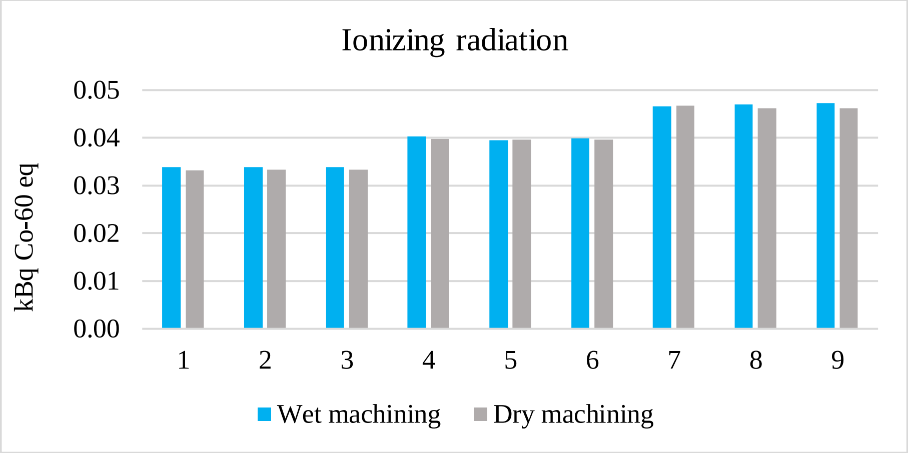


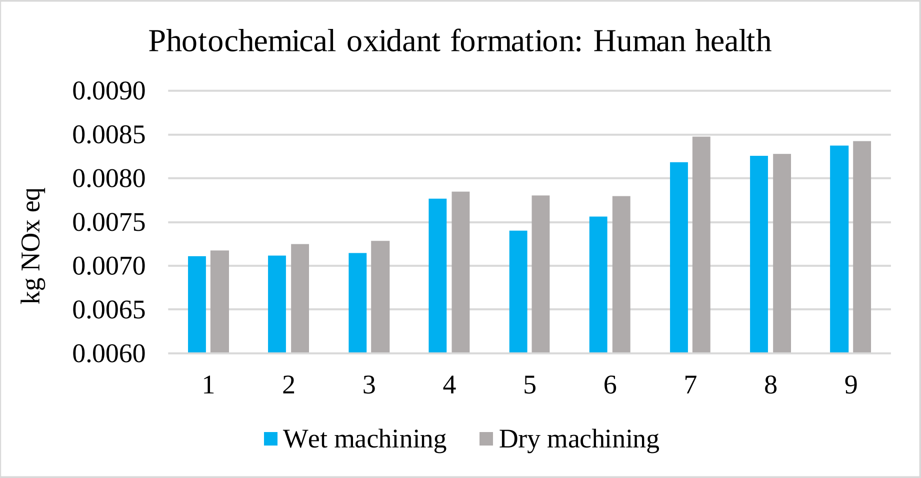
Experiment number 18 (dry machining, n = 1100 rpm, f = 0.20 mm/rev, a_p = 1.10 mm)

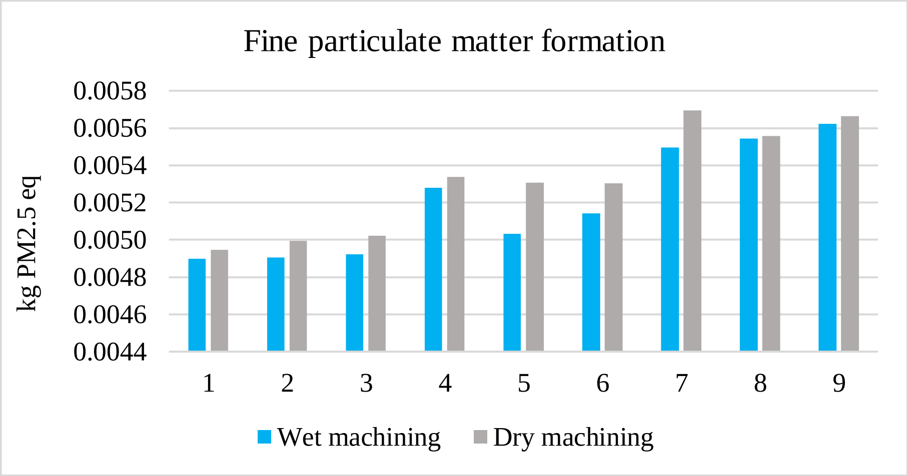


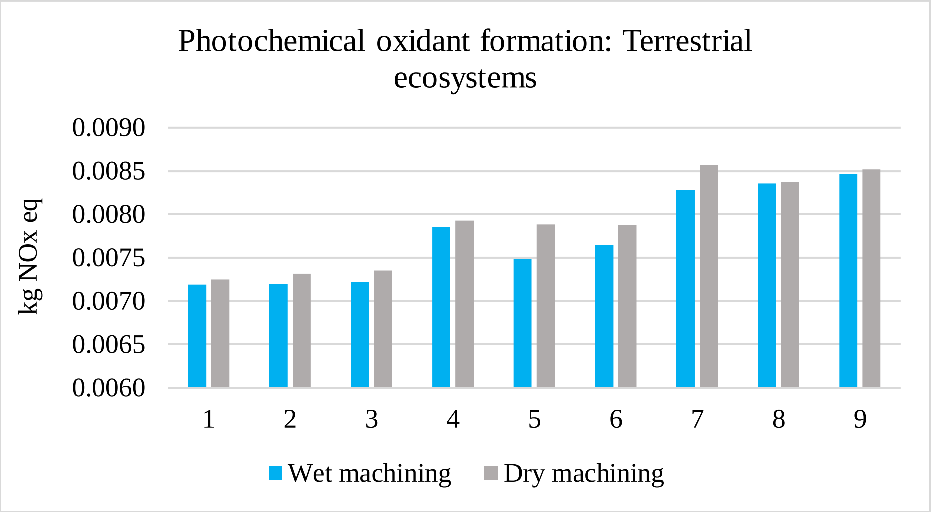
APPENDIX C: VARIATION OF IMPACT CATEGORIES WITH OPERATING CONDITIONS

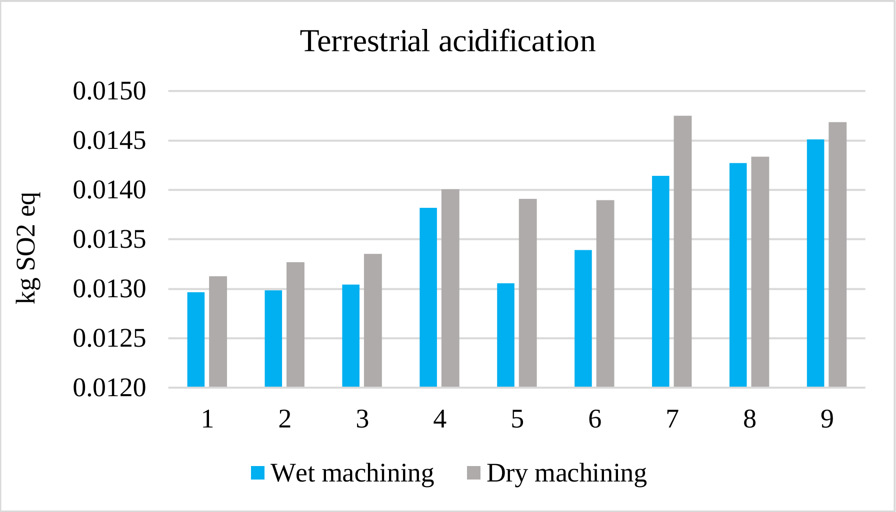

Ozone depletion

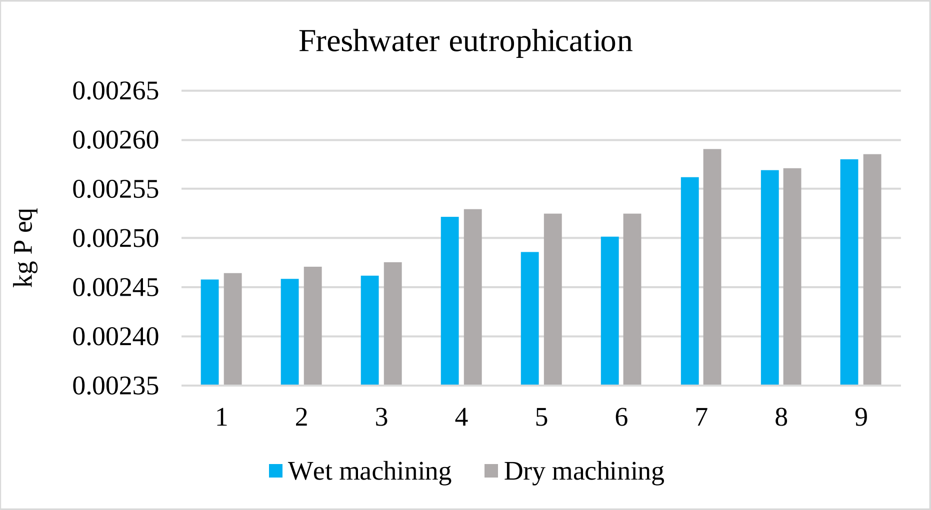

Ionizing radiation

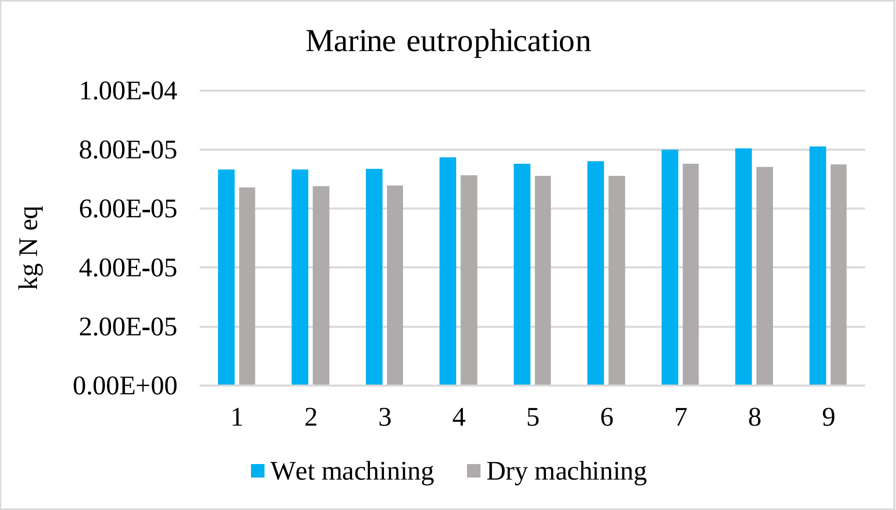

Photochemical oxidant formation: Human health

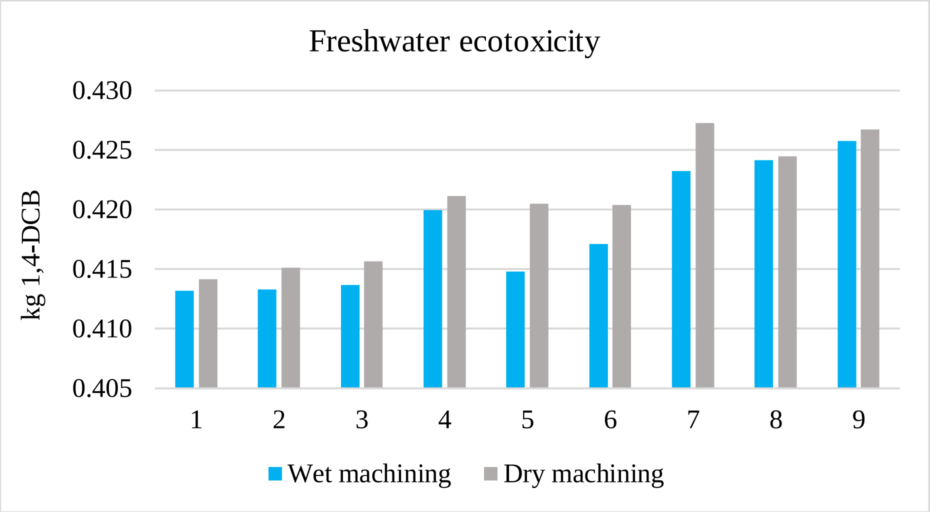

Fine particulate matter formation

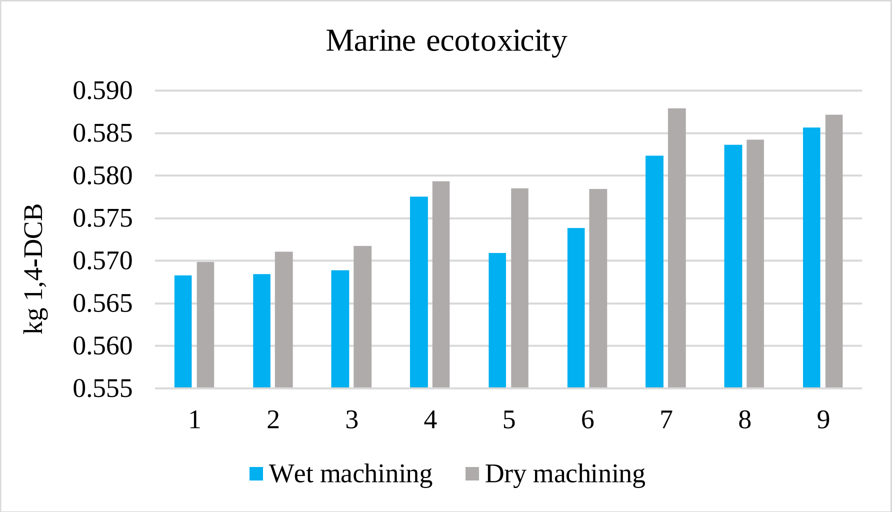

Photochemical oxidant formation: Terrestrial ecosystems
kg NOx eq
0.0090
0.0085
0.0080
0.0075
0.0070
0.0065
0.0060
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

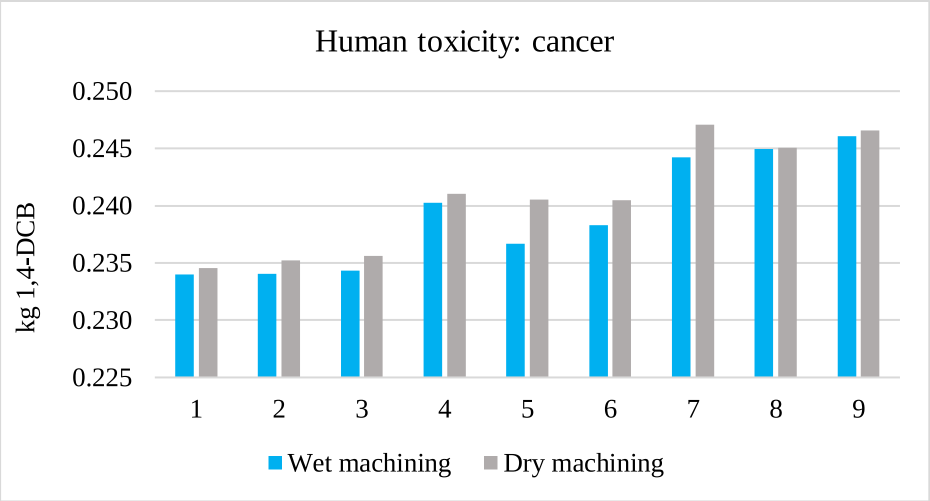

Terrestrial acidification
kg SO2 eq
0.0150
0.0145
0.0140
0.0135
0.0130
0.0125
0.0120
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

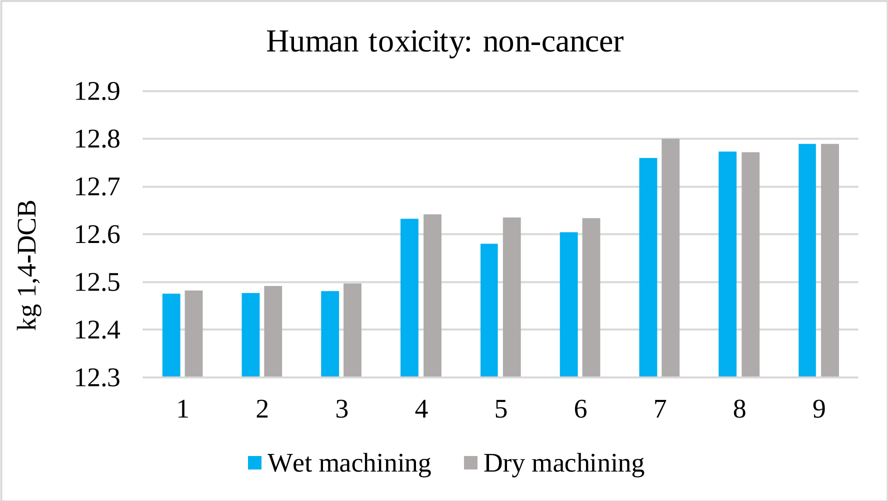

Freshwater eutrophication
kg P eq
0.00265
0.00260
0.00255
0.00250
0.00245
0.00240
0.00235
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

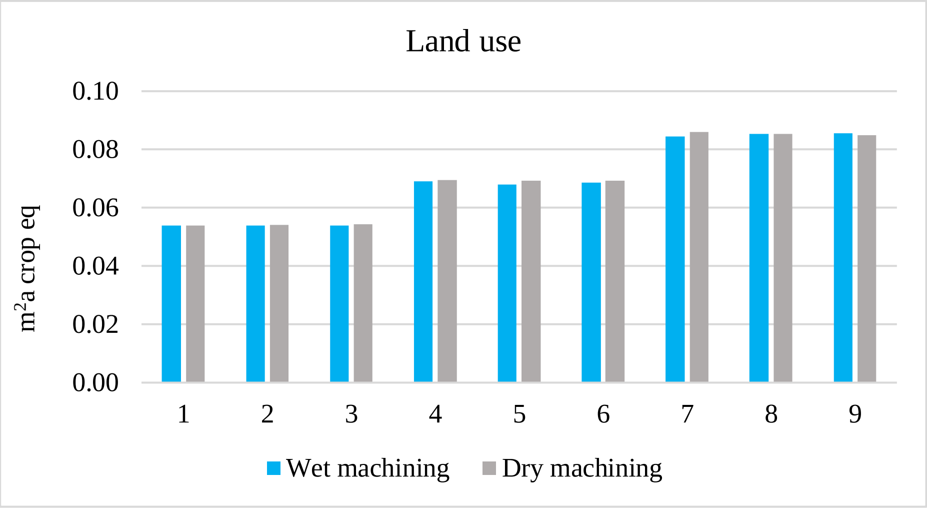

Marine eutrophication
kg N eq
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

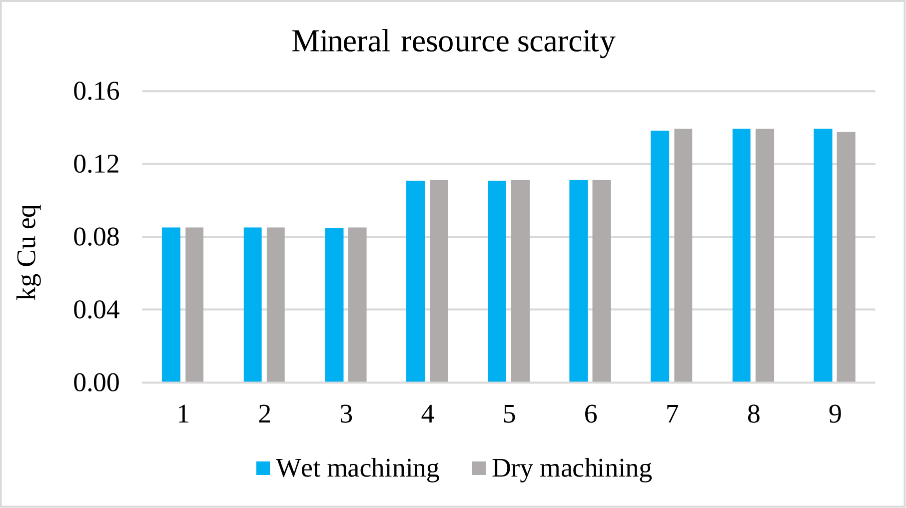

Freshwater ecotoxicity
kg 1,4-DCB
0.430
0.425
0.420
0.415
0.410
0.405
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

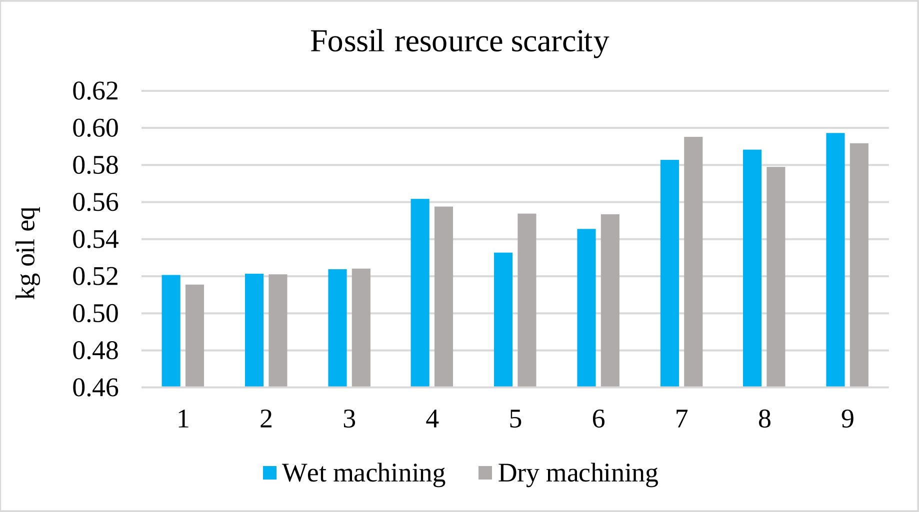

Marine ecotoxicity
kg 1,4-DCB
0.590
0.585
0.580
0.575
0.570
0.565
0.560
0.555
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining

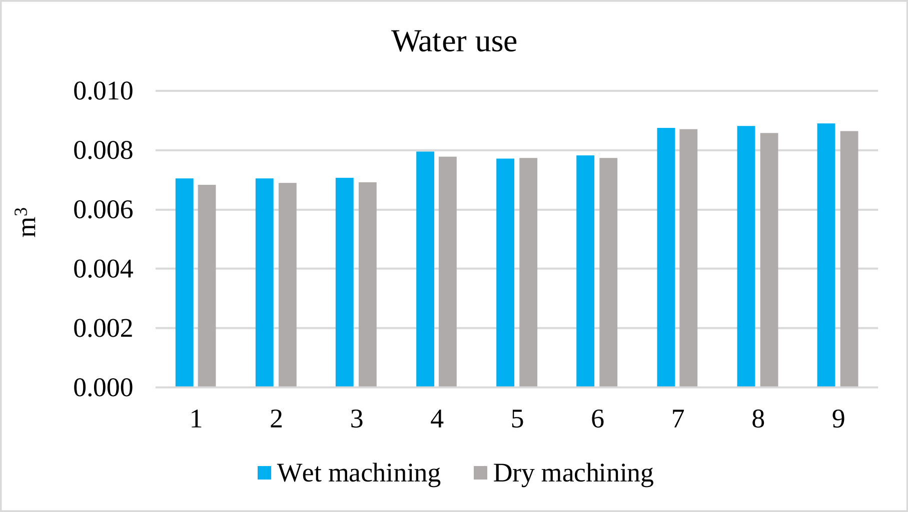

Human toxicity: cancer
kg 1,4-DCB
0.250
0.245
0.240
0.235
0.230
0.225
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining


Human toxicity: non-cancer
kg 1,4-DCB
12.9
12.8
12.7
12.6
12.5
12.4
12.3
1
2
3
4
5
6
7
8
9
Wet machining
Dry machining


Land use
m²a crop eq
0.10
0.08
0.06
0.04
0.02
0.00
1
2
3
4
5
6
7
8
9
■ Wet machining
■ Dry machining


Mineral resource scarcity
kg Cu eq
0.16
0.12
0.08
0.04
0.00
1
2
3
4
5
6
7
8
9
■ Wet machining
■ Dry machining


Fossil resource scarcity
kg oil eq
0.62
0.60
0.58
0.56
0.54
0.52
0.50
0.48
0.46
1
2
3
4
5
6
7
8
9
■ Wet machining
■ Dry machining


Water use
m³
0.010
0.008
0.006
0.004
0.002
0.000
1
2
3
4
5
6
7
8
9
■ Wet machining
■ Dry machining