REDUCING WASTE WITHIN THE HIGH PRECISION MANUFACTURING INDUSTRY TO ACHIEVE UK NET ZERO AND SUSTAINABILITY TARGETS. A CASE STUDY: ELE ADVANCED TECHNOLOGIES.

by

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ABSTRACT

High precision manufacturing (HPM) generates large amounts of waste material due to relying on subtractive manufacturing (SM) processes, such as grinding and electrical discharge machining (EDM). Finding ways to optimise resource use and waste management for these processes is essential to improving the sustainability of the HPM sector. This research used the HPM company ELE Advanced Technologies as a case study. Grinding wheel use was monitored over a three-month period by measuring the remaining diameter of spent wheels. During this time, all grinding operators ($n = 32$) received a questionnaire designed to identify barriers to efficient resource use. Additionally, contaminants within waste dielectric fluid from the EDM process were removed using filtration and centrifugation. Fluid samples were classified as 'untreated', 'filtered', 'centrifuged', 'filtered and centrifuged' or 'clean'. Sample absorption values and microparticle sizes were analysed using UV-Vis and DLS, while the elemental composition of the contaminants was determined using SEM-EDS. GC-MS identified the hydrocarbon structures that composed each sample. During wheel monitoring, very few wheels achieved their minimum diameter (*11.11%*), lack of appropriate training for grinding operators and insufficient provisions for wheel re-use were the main reasons for this. If grinding operators adopted sustainable behaviours, between 1.8 - 6.0 tCO_{2eq} emissions could be saved annually. For EDM, the pollutants chromium VI and nickel II were identified at concentrations of 7.33 mg L^{-1} and 9.40 mg L^{-1} respectively. Centrifugation was the most effective contaminant removal method. 'Centrifuged' samples displayed a significantly lower absorption value at the wavelength maxima than 'filtered' ($p<0.001$). Hydrocarbon structures remained consistent between samples. Overall, the culture at HPM companies affects their carbon footprint and sustainability. Implementing appropriate training and providing opportunity for employees to display sustainable behaviour results in less material waste. For unavoidable waste, removing contaminants can lower the polluting risk and increase opportunity to re-use the waste. These steps improve HPM company's sustainability and reduce their carbon footprint.

Key words: Net Zero, grinding, EDM, emissions, sustainable.

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DEFINITIONS

Grinding wheel:	*A wheel used for the cutting, grinding, or finishing of other objects. Commonly used in manufacturing.*
Part-worn wheel:	*Grinding wheels that can be used re-used.*
Spent wheel:	*Grinding wheels that are ready to be disposed of.*
Dielectric fluid:	*An insulating fluid that is commonly used in the EDM process.*
Clean sample:	*Virgin dielectric fluid sample.*
Untreated sample:	*Dielectric fluid waste from the EDM process.*
Untreated (diluted) sample:	*Untreated sample that has been diluted with the clean sample.*
Filtered sample:	*Untreated sample that has undergone filtration.*
Centrifuged sample:	*Untreated sample that has undergone centrifugation.*
Filtered and centrifuged sample:	*Untreated sample that has undergone filtration and centrifugation.*
CO_2 equivalence:	*A metric measure used to compare the global warming potential of greenhouse gases.*

INITIALISMS

HPM	*High precision manufacturing*
SM	*Subtractive manufacturing*
EDM	*Electrical discharge machining*
UV-Vis	*Ultraviolet-visible spectroscopy*
SEM-EDS	*Scanning electron microscopy and energy dispersive X-ray spectroscopy*
GC-MS	*Gas chromatography mass spectrometry*
DLS	*Dynamic light scattering*

1.0 INTRODUCTION

This research stems from the UK governments commitment to support small- to medium-sized enterprises (SMEs) in their carbon reduction journey, as laid out in the UK's 2050 targets (e.g., The Carbon Plan, 2011; Net Zero Strategy: Build Back Greener, 2021; Powering Up Britain: The Net Zero Growth Plan, 2023). This research has considered how manufacturing companies contribute to pollution of land, water, and air.

1.1 Context

Climate change is one of the most urgent issues being faced today, as highlighted by current temperature records, climate projections, and global warming rates (MET Office, 2022). At the UN Climate Change Conference (COP21), long-term climate change goals were set in the Paris agreement (2015). The most significant of these goals was to substantially reduce CO_{2eq} emissions so global warming could be limited to 2^{o}C this century, while trying to not exceed 1.5^{o}C. This agreement prompted some countries to amend their own climate policies. For instance, the UK government updated their climate change targets when the amended Climate Change Act 2008 [2019 Amendment] was released (2019). The new targets were to significantly reduce CO_{2eq} emissions by 2030, and to have Net Zero carbon by 2050. Despite being one of the first countries to put the requirement for Net Zero CO_{2eq} emissions into domestic law, the UK has failed to implement a large number of policy recommendations from their Climate Change Committee (CCC) and are looking unlikely to meet their 2050 goals because they are behind on their mid-term targets (Marteau, Chater and Garnett, 2021). Due to the UK lacking a fully-fledged and centralised emissions reduction plan, local councils are failing to assist the country in meeting the goals set in the Paris agreement. 75% of UK local councils had issued a climate emergency warning by 2019, and set a date of 2030 to achieve Net Zero, but only 2% produced a delivery plan to demonstrate how this could be accomplished (Gudde *et al.*, 2021). Additionally, the latest CCC report was published in June (2021): The 'Independent Assessment of UK Climate Risk'. This report states that the average UK land temperature has risen by 1.2^{o}C post-industrialisation while emphasising that the UK is struggling to keep up with the pace of climate change, and as a result is not resilient to its impacts. Individual companies are seen as vital for the transition to Net Zero, and there is a belief that they can achieve more ambitious targets than governments (Li, Wiedmann and Hadjikakou, 2020). If UK companies can meet their own climate plans, then the country's Net Zero goals are theoretically achievable (Kuramochi *et al.,* 2020). It is for these reasons that carbon emissions were a focus of this research, and why a case study of a UK-based company was conducted.

A company's carbon impact can be monitored by looking at CO_{2eq} emissions from three different scopes of their business (Tong *et al.,* 2021), which are explained in the Greenhouse Gas Protocol Corporate Standard (2015). Scope 1 CO_{2eq} emissions are produced directly from sources owned by the company. Scope 2 CO_{2eq} emissions are indirect emissions caused by the purchases of utilities, such as electricity and heat. Scope 3 covers indirect CO_{2eq} emissions that occur within an organisations wider value chain. Many companies can monitor their scope 1 and 2 emissions, but the process for monitoring scope 3 emissions is not well established and presents a knowledge gap that is important to fill (Shrimali, 2022). Therefore, this research has contributed to reducing this gap in knowledge by studying the scope 3 emissions of the case study company. This is due to the increasing importance of monitoring scope 3 emissions and having increased responsibility for a product's emissions across its entire lifecycle (Hertwich and Wood, 2018).

The International Standard for assessing a product's environmental impact across its entire lifecycle is ISO14040:2006. Within this standard, the principles and framework for life cycle assessments (LCAs) are described. This includes definition of the goal and scope of the LCA (which ensures all LCAs have clearly defined boundaries), the life cycle inventory analysis (LCI) phase (for estimating the raw material and energy requirements, solid wastes, and environmental pollutants), the life cycle impact assessment (LCIA) phase (for the evaluation of environmental impacts from LCI estimates), the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. In summary, ISO14040 provides information on a standardised methodology that enables analysis of a product's environmental impact, the lifecycle assessment (Finkbeiner, 2014). This methodology presents excellent opportunities for socio-economic performance improvements as well as better assessment of progress towards sustainability targets (Johnstone and Hallberg, 2020), which is why an LCA has been used within this research. LCAs can assist in calculating the carbon footprint of a manufactured product by monitoring environmental factors, such as greenhouse gas emissions, at different stages in the products lifecycle and generating a global warming potential (GWP) for the product (Kendall, 2012). The most complete LCAs encompass all emissions from a products material extraction through to waste disposal (cradle-to-grave), which facilitates scope 1, 2, and 3 monitoring (e.g., Salah and Romanova, 2021) and provides a complete picture of a products carbon output. Another benefit of LCA is that they can be designed to identify impacts across a range of different environmental impact categories (e.g., Pfister *et al.*, 2016; Amicarelli, Lagioia and Bux, 2021). While calculating GWP is highly important for achieving Net Zero, understanding impacts on other environmental factors, such as freshwater or marine aquatic ecotoxicity, is crucial for achieving complete sustainability. Therefore, LCAs are important for companies that aim to become more sustainable and are a useful method for quantifying environmental impacts of their products and process, making them a vital part of this research when establishing the environmental impact of the case study company.

1.2 Case study company: ELE Advanced Technologies

The case study for this research is ELE Advanced Technologies (ELE). This company conducts high precision manufacturing (HPM), which typically refers to machining parts with tolerances in the single-digit micron range. ELE was chosen as the case study due to being an established HPM company and produces over 200,000 unique parts with volumes of 50 to 20,000 units per year. ELE began as Earby Light Engineers in 1955 with the purpose of supplying compressor blades for Rolls Royce. They changed their name to ELE Advanced Technologies in 2000, before opening their Colne facility and focussing on production of industrial gas turbine and aero-engine components in 2004. Since then, they have continued to grow into a global supplier of these components, including turbine blades and vanes, and they are currently opening a new headquarters in Nelson. ELE assist their customers in the design and production of their required parts, utilising cutting-edge technology and the latest advancements in precision manufacturing. This includes the use of electrical discharge machining (EDM), STEM, capillary, and laser drilling, as well as multi-axis milling and viper grinding. Their work within the manufacturing industry was recognised at the 2022 Red Rose Awards, where they won the 'Innovation', 'Made in Lancashire', and 'Scale-up' awards.

1.3 Scope of study

This study is about improving sustainability in the manufacturing sector, this sector is chosen because it is one of the UK's four highest greenhouse gas emitting sectors (Office For National Statistics, 2022). Therefore, ELE Advanced Technologies was used as the case study to highlight some of the challenges this sector faces.

1.4 Thesis structure

This structure of this thesis is as follows: first, a literature review was conducted to establish current knowledge regarding the environmental impacts of HPM companies and identify areas that require further research. This is followed by the research aim, objectives, and research questions being addressed before explaining the methodology that has been used to answer them. Study chapter one then establishes how to reduce the carbon emissions from the key HPM process of grinding, with greater detail into the methods and results obtained from this part of the research. Next, study chapter two identifies how to reduce pollutants from another key HPM process of electrical discharge machining (EDM), again with detailed methods and results. Following this, the outcome of research is discussed, which highlights how each research question has been addressed, before concluding with recommendations and ideas for further research.

2.0 LITERATURE REVIEW

High precision manufacturing (HPM) has been an integral part of engineering for many decades, with the degree of precision capable by manufacturing machines being continually scrutinised (e.g., Taniguchi, 1983; McKeown, 1987; Zhang, Z., Yan and Kuriyagawa, 2019). Nowadays, HPM can achieve an accuracy within 1-5 µm, making it a highly accurate method of manufacturing (Zhang, Z., Yan and Kuriyagawa, 2019). Therefore, HPM is performed for parts that require consistent and exact specifications to be met. For instance, HPM is required to produce turbine and aero-engine parts, such as blades and vanes. While HPM is a reliable form of engineering, it does cause high levels of CO_{2eq} emissions due to the energy requirements of, and waste generated by, the machines used during the manufacturing process (Watson and Taminger, 2018).

HPM has traditionally relied on subtractive manufacturing (SM) processes, where a block of material is carved or machined to become the desired part (e.g., Kapil *et al.*, 2017). Due to the waste SM generates there is a need for manufacturers to adopt more sustainable approaches, such as additive manufacturing (AM) (Torres-Carrillo *et al.*, 2020). AM is a type of 3D printing and a form of manufacturing that integrates advanced machinery, materials, computing, and numerical control to build up the desired part by layering the material (Shi *et al.*, 2021). Recent studies have highlighted AM as the environmentally friendly alternative to SM (e.g., Watson and Taminger, 2018; Siva Rama Krishna and Srikanth, 2021), however, the technology is not yet being consistently used across the manufacturing industry due to limitations regarding pace, cost, and quality of production (Altıparmak *et al.*, 2021). Many research projects are focussed on filling this knowledge gap and making AM an effective technique for manufacturing (e.g., Altıparmak *et al.*, 2021; Tang *et al.*, 2022), however, SM remains a widely utilised manufacturing technique and causes HPM to be highly wasteful (Paris *et al.*, 2016).

2.1 High precision manufacturing operations: Grinding

Grinding is an SM technique used within HPM to give manufactured components the desired shape and finish (Souza and da Silva, 2019). This process is responsible for the generation of metal and alloy waste in the form of a powder, which can contain large quantities of valuable alloy. Recovery of this material would help to increase the environmental sustainability and cost efficiency of HPM (Wang, Yunting, Xue and Zhang, 2021). Additionally, grinding wheels deteriorate and decrease in performance during the grinding process (Souza and da Silva, 2019). This results in the grinding wheel being replaced and discarded as waste, which has negative impacts for a company's carbon footprint even if the wheel is recycled (e.g., Catalano *et al.*, 2022). A study by Elmaraghy, Nada and Elmaraghy (2008) modelled human error probability in the manufacturing process and found that human involvement allows higher levels of flexibility during manufacturing but increases the likelihood of an error. These errors would result in a loss of time, money, and resources for the affected company. Therefore, reducing reliance on operator judgement could lead to fewer errors in the manufacturing process and less waste being generated. One potential area for human error during the grinding process is the wheel change, because wheels could be removed before they have been used for their maximum lifespan, causing viable grinding wheels to be discarded as waste. There has been limited research into how human error affects the grinding process (e.g., Santiasih and Ratriwardhani, 2021), but the way a grinding operator judges when a wheel change is required has not been thoroughly investigated. Consequently, the accuracy of operator judgement during the grinding process is an important area to research, as this could have significant implications for the sustainability of a HPM company.

One method for reducing human error in the manufacturing process is through appropriate training. La Fata *et al.*, (2023) found that training and experience are the factors that most significantly reduce human error and improve the reliability of operators within the manufacturing sector. Additionally, sustainability training has been shown to increase environmental awareness of employees, which has a range of benefits, such as reducing the environmental impact of an individual (Birou, Green and Inman, 2019). Therefore, it is important to establish the level of understanding grinding operators have regarding the sustainability of the grinding process. By doing this, knowledge gaps and opportunities to educate HPM company employees could be highlighted, allowing training programmes to be designed that address employee needs so that they participate in sustainable work practices (Machnik-Słomka and Kłosok-Bazan, 2017). ISO14001 should be followed when planning employee training because this provides detailed guidance for the implementation of an effective environmental management system. This would allow companies to achieve their sustainability targets through better communication of policies and effective training (Widiatami, Pitaloka and Nurkhin, 2022). For instance, the addition of sustainability training could reduce human error during grinding wheel changes, meaning there is potential for employee education to reduce waste and save HPM companies money while also reducing their carbon footprint. Therefore, assessing the sustainability awareness of grinding operators is a crucial step for improving the sustainability of the grinding process. Questionnaires could be an effective method for establishing if sustainability training is required, as well as identifying any behaviours that could impact the sustainability of the grinding process (e.g., Liu *et al.*, 2022). However, questionnaires do have the limitation of not always capturing an individual's thought process, so reasoning behind answers/behaviours can be difficult to identify. To contextualise any findings from questionnaires, behavioural theories should be considered as these can increase the understanding about why specific behaviours are shown.

2.2 Behavioural Theories

A behavioural theory attempts to provide a reasoned explanation for human behaviours by analysing the internal and external factors that influence an individual's actions. Each theory provides a different perspective for an individual's decision-making process, some of which can be conflicting (e.g., Smith, 1976; Schwartz, 1977). Therefore, a behavioural theory that considers a wide range of influences allows human behaviours to be contextualised more accurately.

Purpose-oriented theories suggest a person's actions all serve the purpose of achieving goals set by the individual. Rational Choice Theory (RCT) is an early purpose-oriented theory that was proposed by political economist and philosopher, Adam Smith (1976), and is the main paradigm for studies modelling social, economic, or individual behaviours (e.g., Stocké, 2019). The premise of RCT is that rationality gets determined by an individual through the balancing of costs and expected benefits they will receive from a specific action (Ogu, 2013). According to Ogu (2013) this means that RCT is a useful theory for explaining seemingly irrational behaviours that would appear to have little reasoning to an observer. However, RCT is an inherently selfish theory that suggests an individual is only likely to act in their self-interest (Zey, 2015). This presents a major flaw within the theory, as pure altruistic behaviours serve no benefit to an individual and can even be performed with great cost, which contradicts the selfish perspective taken by RCT (Andreoni, 1990; Feigin, Owens and Goodyear-Smith, 2014). From an environmental viewpoint, this means that RCT cannot explain why an individual may exert more time or energy for an action that allows their behaviour to be more environmentally sustainable. Additionally, the rationality of an individual's choice is largely unaffected by their environment because only intrinsic factors are considered; therefore, external factors have little impact on decision making (Kroneberg and Kalter, 2012). By ignoring social factors that could influence decision making and actions, RCT lacks the nuance required to explain human behaviour in a wide range of contexts (Ogu, 2013). Despite these flaws, RCT is well-established within economics because behaviours that lead to an individual's economic success often align with RCT (e.g., Herfeld, 2020), meaning that it remains prominent in research today. Therefore, the strength of this theory cannot be discounted, which is why RCT has inspired many other behavioural theories, such as the Theory of Planned Behaviour (TPB).

TPB suggests that an individual considers the intention of their behaviour by assessing rationality through the perspective of 'attitude', 'subjective norms' and 'perceived behavioural control', before deciding on the behaviour that will most benefit them (Ajzen and Kruglanski, 2019). 'Attitude' refers to the individuals evaluation and rationality assessment of a behaviour (similar to that discussed in RCT). The 'subjective norm' refers to how much emphasis an individual places on societal expectations and the belief of those around them about whether they should or should not perform a behaviour. Finally, 'percieved behavioural control' is an individuals belief about the presence of factors that could impede or facilitate their performance of a behaviour. These three factors shape an individuals intention to perform a behaviour, which ultimately shapes the behaviour itself (Chao, 2012). The main variables of TPB are summarised in *figure 1*.

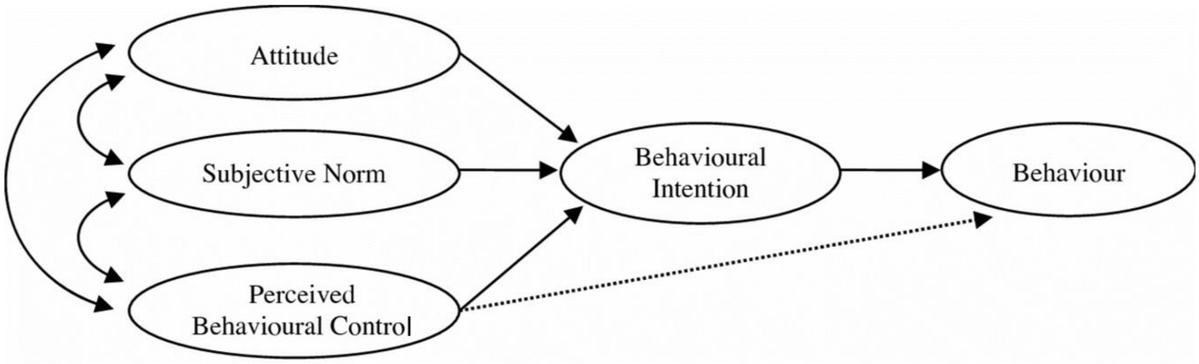

Figure 1: Schematic diagram of the Theory of Planned Behaviour (TPB). Diagram originated from Chao (2012).

TPB considers behaviour in the context of an individual's environment, which could explain why an individual displays behaviour that has greater direct benefit for others than themselves, because 'subjective norms' may cause social benefits to outweigh personal costs (e.g., Teng, Wu and Liu, 2015). Furthermore, TPB focusses on target setting (Ajzen, 2020), and is widely used in psychology when trying to develop socially positive behaviours within an individual, such as recycling, conservation, and other pro-environmental behaviours (Steinmetz *et al.*, 2016; Yuriev *et al.*, 2020). However, this theory fails to address the intention-behaviour gap, which occurs when an individual does not perform an intended action (Grimmer and Miles, 2017). While Ajzen (2020) explains possible reasons for the intention-behaviour gap within the context of TPB, such as forgetting their intention or a change of intention, the fact remains that intention is a weak indicator of behaviour and TPB may not present a comprehensive explanation for why a behaviour occurred.

Another branch of purpose-oriented theory are pro-social theories, such as the Norm Activation Theory (NAT). According to Schwartz (1977), decision making is determined through balancing different moral considerations. Within this theory, an individual will construct 'personal norms' from four situational factors and two personality trait activators, which influences how morally obligated they feel to perform a behaviour. The four situational factors are: 1. *Awareness of need*, which refers to how aware an individual is to the needs of another individual or the environment. 2. *Situational responsibility*, referring to the extent the individual feels responsible for that need. 3. *Efficacy*, a judgement of the extent of action required to alleviate that need. 4. *Ability*, an individual's perception about their capability and availability of resources for performing the required behaviour. The two personality trait factors are: 1. *Awareness of consequences*, referring to how perceptive an individual is to situational cues that indicate the needs of others. 2. *Denial of responsibility*, referring to an individual's inclination to shift responsibility for the welfare of others or the environment away from themselves. The structure of NAT is summarised in *figure 2* below.

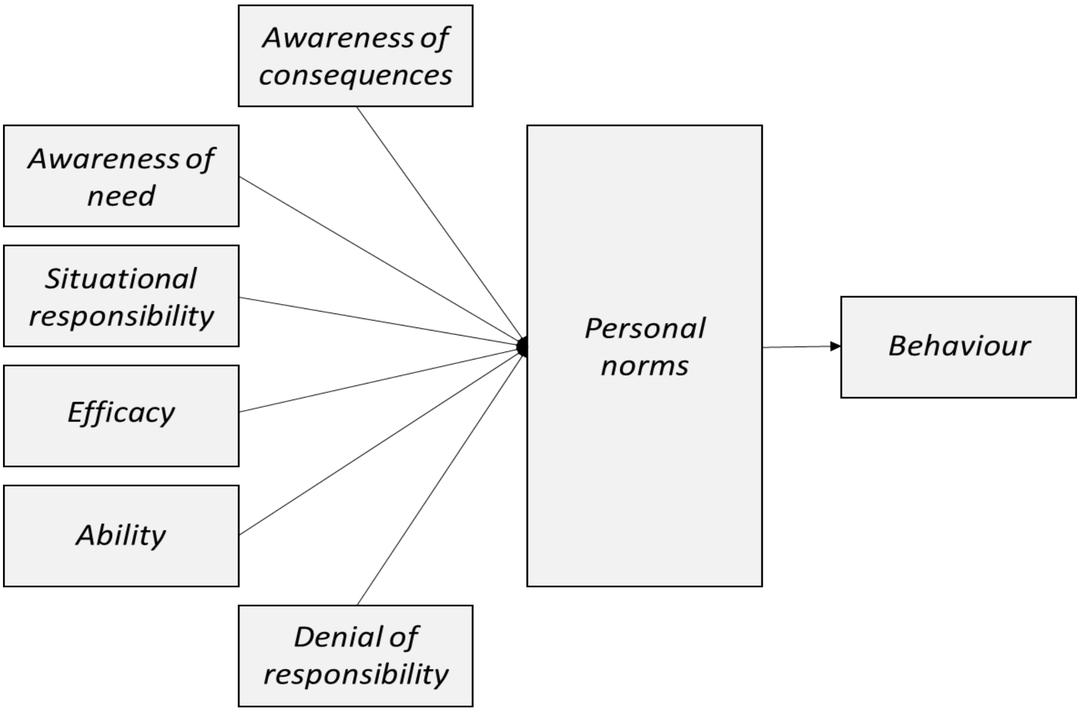

Figure 2: Norm Activation Theory (NAT) schematic overview. Adapted from Harland, Staats and Wilke (2007).

In the Harland, Staats and Wilke (2007) study, the viability of using NAT to explain pro-environmental behaviours was explored. Previous studies that have used NAT to investigate the origins of pro-environmental behaviour used a simplified version of the theory and focussed on the influence of only two situational factors i.e., 'awareness of need' and 'situational responsibility' (e.g., Vining and Ebreo, 1992; Gärling *et al.*, 2003), but Harland, Staats and Wilke (2007) considered the influence of each factor within NAT and found that this theory is capable of explaining an individual's willingness to perform pro-environmental behaviours when all influencing factors are considered (*figure 2*). However, NAT did have varying levels of success when being applied to different pro-environmental behaviours, e.g., saving household water and volunteering, which may indicate that the theory is inconsistent and unable to be applied to all pro-environmental behaviours (Harland, Staats and Wilke, 2007). Furthermore, NAT fails to provide an explanation for 'over-imitation', which occurs when an individual places great emphasis on societal expectations and will conform without consideration to the moral implications of their actions (Hoehl *et al.*, 2019). The desire to fit with societal expectations is better explained by the TPB than by the NAT, presenting a potential weakness with using this theory to explain the presence (or absence) of pro-environmental behaviours in grinding operators during the grinding process because it could be unclear whether grinding operator behaviours are due to active moral choices or simply being performed to conform with other operators.

A behavioural theory that explains how an individual can balance selfish rationality (from RCT), societal expectation (from TPB), and moral decision making (from NAT) is necessary for contextualising grinding operator decision making. This is where the Social Practice Theory (SPT) could be beneficial. SPT is an alternative to the purpose-oriented behavioural theories and looks at how individuals can adapt behaviours to a range of different scenarios (Penuel *et al.,* 2017). The Penuel *et al.,* (2017) study uses SPT to explain how an individual can change their behaviour as new possibilities become available, with SPT allowing them to learn from the consequences of these actions and adjust their behaviour accordingly. This means that an individual is constantly using their own rational and moral judgement within the context of their society and environment to determine if their behaviours were appropriate and should be continued. Therefore, behaviours can be constantly adjusted to fit the demands of a societal structure (Penuel *et al.,* 2017). This has been shown to have positive impacts on the adoption of pro-environmental behaviours, as societal changes were able to influence an individual's attitude and personal norms (Hargreaves, 2011). Overall, SPT encapsulates more variables that can influence behaviour than the purpose-oriented theories: RCT, TPB and NAT. While this does increase the complexity of SPT and can make the theory difficult to apply in practice (Jackson, 2005), this theory can incorporate rationality, sociology, and morality (*table 1*) within the greater context of an individual's changing environment, making it a highly useful theory when examining grinding operator behaviours.

Table 1: Summary of variables that are considered by each behavioural theory.

Behavioural Theory	**Rationality**	**Sociology**	**Morality**	**Literature**
Rational Choice Theory	✔			(Kroneberg and Kalter, 2012; Ogu, 2013)
Theory of Planned Behaviour	✔	✔		(Chao, 2012; Teng, Wu and Liu, 2015)
Norm Activation Theory		✔	✔	(Harland, Staats and Wilke, 2007; Hoehl *et al.*, 2019)
Social Practice Theory	✔	✔	✔	(Hargreaves, 2011; Penuel *et al.*, 2017)

2.3 High precision manufacturing operations: Electrical discharge machining

Another subtractive manufacturing technique used by companies within the high precision manufacturing sector is electrical discharge machining (EDM). EDM is a non-traditional material removal process that is used to erode conductive materials with thermoelectric energy (Abu Qudeiri *et al.*, 2018). One example of EDM's application is for drilling cooling holes into turbine blades (Kliuev *et al.*, 2016; Li, C. J. *et al.*, 2016). The EDM process facilitates highly accurate machining for parts of great complexity, with the additional benefit of the EDM tool (electrode) not needing to contact the part being modified (workpiece) (Mohd Abbas, Solomon and Fuad Bahari, 2007; Hsieh *et al.*, 2007). By the tool not touching the workpiece, the manufactured product is then free from residual stress (Kansal, Singh and Kumar, 2007). The schematic diagram of EDM is shown in *figure 3*. Performance of EDM is controlled by several factors; discharge voltage, discharge gap, peak current, polarity, pulse on time, and pulse off time (Abu Qudeiri *et al.*, 2018). The discharge voltage refers to the average voltage in the gap between the electrode and workpiece (a.k.a. the discharge gap), higher discharge voltages are required for materials of low electrical conductivity (e.g., Yang *et al.*, 2018) and vice versa for high conductivity materials. Peak current is the amount of power required for discharge machining and is highly influential on performance as it determines the spark energy of the EDM process (Nguyen, P. H. *et al.*, 2020). Polarity refers to the charge of the electrode and workpiece. These are opposite charges to one another, with the electrode typically being positively charged (Abu Qudeiri *et al.*, 2018), although this is not always the case (e.g., Nair *et al.*, 2019). Finally, the pulse on and off times refer to the amount of time that the electrode is and is not discharging. These factors influence the material removal rate and the stability of the process (Ramakrishnan and Karunamoorthy, 2008; Kumar, S. *et al.*, 2009).

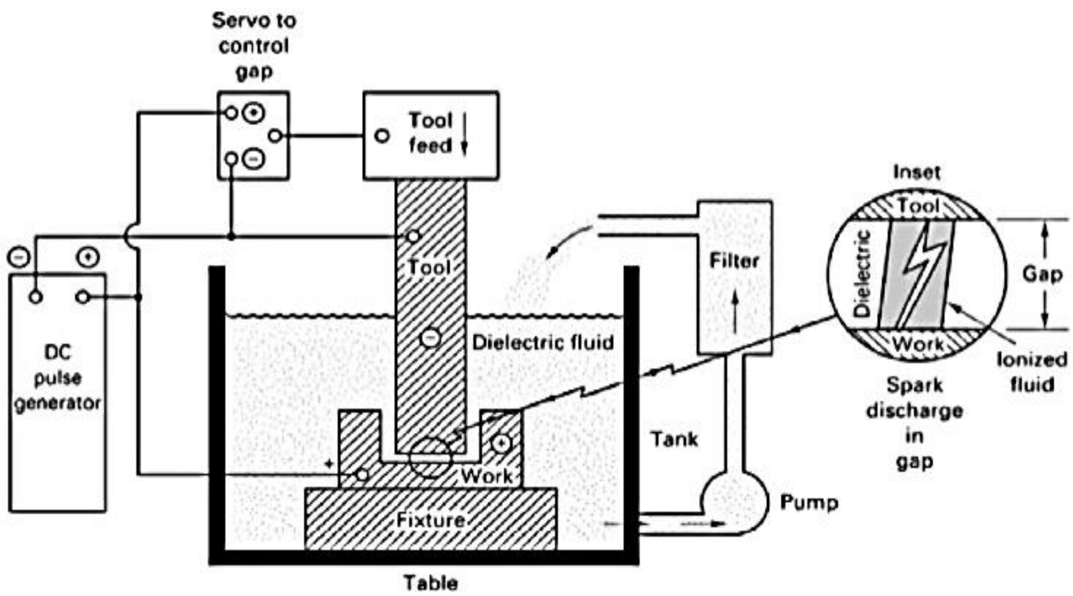

Figure 3: Schematic diagram of sinking Electrical Discharge Machining (EDM), displaying the key components of an EDM machine, and highlighting the discharge gap (Kumar and Dhanabalan, 2019).

EDM requires a dielectric medium to ensure the process runs optimally (Singh, A. K. *et al.,* 2018). Different forms of dielectric are favoured by the five variations of the EDM process: sinking (*figure 3*), wire, micro, powder-mixed, and dry (Qudeiri *et al.*, 2020). According to Bhattacharyya and Doloi (2020), the type of dielectric used significantly influences the environmental impact of EDM. Sinking EDM typically requires the tool and workpiece to be submerged in hydrocarbon oil-based dielectric fluids. These dielectrics offer high performance but are the least environmentally friendly and can generate aerosols or hazardous gas which could impact operator health (Valaki, Rathod and Sidpara,2018). There is a requirement for less harmful alternatives to this dielectric, which current research is attempting to achieve (e.g., Mishra and Routara, 2020). Vegetable oil-based bio-dielectrics have shown promise (e.g., Yadav, A. *et al.*, 2021), but these are not yet commercially used. Secondly, water-based dielectrics are widely used in wire and micro EDM (Bhattacharyya and Doloi, 2020). This is the most environmentally friendly dielectric currently being utilised and offers wire and micro EDM higher material removal rates than hydrocarbon oil-based dielectric (Nguyen, M. D., Rahman and Wong, 2012). However, a water-based dielectric is considered inappropriate for sinking EDM due to causing higher tool wear and poorer performance (Bhattacharyya and Doloi, 2020). Lastly, dry EDM utilises gaseous dielectrics, such as air and oxygen. Gaseous dielectrics would be more environmentally friendly than dielectric fluids and are the subject of current research (Wang, Xiaolong and Shen, 2019; Yadav, V. K., Kumar and Dvivedi, 2019), however, the use of gaseous dielectrics still presents technical issues that require solutions before they can be commercially used (Bhattacharyya and Doloi, 2020). Overall, EDM processes that require hydrocarbon oil-based dielectric fluid result in harmful air pollutants being released into the atmosphere (CO, NO, NO_2, NO_x) (Dwivedi and Choudhury,2018), while also posing greater risk of water and land pollution following disposal than deionised water or bio-dielectric fluids (Leão and Pashby, 2004; Pellegrini and Ravasio, 2020). Furthermore, the importance of an optimised dielectric control system cannot be overstated, these systems are responsible for the continued re-use of dielectric fluids and poor system management can result in increased toxic waste (Bhattacharyya and Doloi, 2020; Baroi, Jagadish and Patowari, 2022). The dielectric system consists of the dielectric fluid, the circulating system (reservoirs, pump, filters, flow control unit), and the delivery device used to guide the fluid (*figure 3*). Changes within this system can affect EDM performance, for example, flow rate of the dielectric fluid requires optimisation as it affects speed of debris flushing (Fujiki, Ni and Shih, 2009; Gholipoor, Baseri and Shabgard, 2015). Therefore, optimising a manufacturer's EDM dielectric control system, particularly within the circulatory system, could be an effective way to minimise waste of environmentally damaging dielectric fluids.

2.4 Waste Management

Effective management of waste is vital when aiming to reduce negative environmental impacts (Sauve and Van Acker, 2020). In 1975, the European Union's Waste Framework Directive introduced the concept of the waste hierarchy. This detailed the ways in which waste should be handled to minimise it's impacts, it is ordered from most preferential action to least: waste prevention, re-use, recycling, recovery, and responsible disposal (Teigiserova, Hamelin and Thomsen, 2020).

While 'responsible disposal' is the last step of the waste hierarchy, it is essential that sources of contamination are removed from unavoidable waste. Without this, harmful pollutants can be inadvertently released into the environment. For instance, waste fluid produced during high precision manufacturing (HPM), such as dielectric fluid from EDM, can result in environmental damage unless properly treated due to the presence of micropollutants, such as heavy metals (Adejumoke, 2018; Leppert, 2018). Therefore, it is important to remove all contaminants from the waste to prevent issues such as soil and water pollution. Removal of these contaminants requires waste treatment plants, but these can be major contributors to climate change due to the energy intensive nature of their work (Law *et al.*, 2012; Panepinto *et al.*, 2016), which contributes to a HPM company's scope 3 carbon emissions. To ensure that downstream emissions are minimised, and HPM companies have increased accountability for their carbon emissions, it is crucial that contaminants are removed from manufacturing waste prior to reaching waste treatments plants (Bhatia *et al.*, 2011; Hertwich and Wood, 2018).

Removing contaminants can be done through physical, chemical, or biological methods (e.g., Tortora *et al.*, 2016). Biological methods have demonstrated huge potential for contaminant removal and have proven successful when removing heavy metal contaminants. These methods include biosorption (Priya *et al.*, 2022), activated sludge (Buaisha, Balku and Yaman, 2020), and trickle filtration (Lee *et al.*, 2021), and present great opportunities for waste treatment due to being highly effective and environmentally friendly. However, biological waste fluid treatment is not always an accessible option for small- to medium- sized enterprises (SMEs) in the HPM industry due to requiring a large amount of space and specialist knowledge to operate and maintain (Gunatilake, 2015). Physical methods, such as filtration and centrifugation, possess the advantages of being much easier to perform, requiring less space, and having lower installation costs, making them a more accessible waste treatment technique for SMEs to adopt (Gunatilake, 2015). Chemical techniques are also highly effective as they allow for the targeted removal of contaminants within waste material (e.g., Thiounn and Smith, 2020). However, as demonstrated by the Thiounn and Smith (2020) study, the chemical or elemental composition of the contaminants must be known prior to starting waste treatment to allow optimal contaminant removal. Enhancing physical separation techniques with chemical methods could present excellent opportunity to achieve efficient waste management for HPM companies, due to the combined benefits of being low cost, highly selective, and having low spatial requirements. A study by Zhou *et al.*, (2023) found that filtration efficiency could be improved by using chemical compounds, because a selective layer could be added into the filtration process to enable targeted contaminant removal. The extent to which this can be applied within HPM must be explored further because this presents an opportunity for SMEs in this industry to better manage their waste and to increase their environmental sustainability. For now, physical separation techniques appear to be the most viable waste management option for these SMEs as they present the easiest and most cost-effective methods (*table 2).*

Table 2: Advantages and disadvantages of each waste management technique.

Waste Management Technique	Advantages	Disadvantages	Literature
Biological	1. Highly effective contaminant removal 2. Environmentally friendly	1. High set-up and operating costs 2. Large spatial requirement 3. Requires specialist knowledge to operate and maintain	(Gunatilake, 2015; Priya *et al.*, 2022)
Physical	1. Wide range of applications 2. Able to remove nanoparticles 3. Low set-up and running cost 4. Low spatial requirements	1. Untargeted contaminant removal	(Gunatilake, 2015)
Chemical	1. Allows targeted removal of contaminants 2. Could increase effectiveness of physical techniques	1. Chemical composition of contaminants must be known	(Thiounn and Smith, 2020; Zhou, Z., Lu, Sun and Wang, 2023)

Centrifugation is a physical waste management technique that can isolate extremely small contaminants within waste fluids, such as microplastics or heavy metals (Qiu *et al.*, 2016; Hildebrandt *et al.*, 2019; Jianbao, Shunqun and Lihang, 2021), by rapidly spinning the sample and generating extremely high centrifugal force that separates particles within a solution. Particles of a density higher than the solvent will sediment and particles of lower density than the solvent will float, the greater the difference in density between the particle and the solvent, the faster the sedimentation/floatation rates (Peters and Evans, 2016). If the particle is isopycnic (of the same density as the solvent) then it does not move. The choice of centrifugation method is dependent on the nature of the sample being treated, differential pelleting and rate-zonal centrifugation are two methods that separate the contaminants based on size, while isopycnic centrifugation separates based on particle density (Rickwood and Graham, 2015). During rate-zonal and isopycnic centrifugation, the sample particles form distinct layers within the solvent which makes them useful analytical techniques, whereas differential pelleting separates the solution into the supernatant and a pellet, consisting of layered particles from the sample (Rickwood and Graham, 2015). Therefore, differential pelleting is the most appropriate centrifugation method for contaminant removal, as all the contaminants become concentrated at the bottom of the waste fluid making them easier to extract.

Filtration is another physical method of waste fluid treatment that has a wide range of applications, this method involves the use of filtration membranes and can be used to remove micro- or nanoparticles. Current literature has explored the benefits of various forms of filtration and has found that filtration is capable of being highly effective for removing contamination from waste fluid, which can reach an effectiveness level of 90% (Gunatilake, 2015). Dynamic membrane filtration can remove microparticle contaminants while lowering the energy requirements and associated costs of waste fluid treatment (Li, L. *et al.*, 2018), and ultrafiltration can remove nanoparticles like silt and bacteria to achieve high levels of contaminant removal (e.g., Hembach *et al.*, 2019). However, an issue found with filtration is that the filter membranes are susceptible to clogging when in contact with larger contaminants and this can reduce their filtering efficiency (Krahnstöver, Hochstrat and Wintgens, 2019). This would present issues for HPM processes like EDM which require microparticle contaminants to be removed from dielectric fluid, such as fine metal shavings. To overcome this issue, a filtration series could be set up to remove progressively smaller contaminants, ensuring contaminants of larger size are removed prior to reaching the finer filtration membranes (e.g., Conkle, Báez Del Valle and Turner, 2018). By doing this, more effective contaminant removal can be achieved, which keeps the conductivity of dielectric fluid low and increases the usable lifespan of the fluid in the EDM process (Yueqin *et al.,* 2017). Lastly, filtration and centrifugation have also proven effective in combination for the removal of contaminants from waste sewage by Wang *et al* (2018). Therefore, these techniques could offer a simple and effective way to remove contaminants from dielectric fluid waste, enabling safer disposal of waste fluid as well as potential recovery of valuable materials within the waste.

2.5 Waste Composition

Understanding elemental and chemical composition of waste material is vital for effective waste management. A lack of awareness can have serious implications for the type of waste treatment being performed, the way that waste gets disposed, and the potential for waste recovery or recycling (Bisinella *et al.,* 2017). Furthermore, contributing towards a circular economy and generating accurate lifecycle assessments are impossible if the waste materials are unknown (Pivnenko and Astrup, 2016; Bisinella *et al.,* 2017). Therefore, the composition of waste has significant ramifications for a company's sustainability and is crucial information for all companies that are trying to achieve Net Zero.

To develop an understanding of the waste composition, various analytical techniques can be used. The cheapest and simplest option is optical microscopy, but this is an unreliable method and could result in the misidentification of contaminant particles (Eriksen *et al.,* 2013). According to Renner *et al.,* (2018), the four techniques that are most important when characterising fluid contamination are: Fourier Transmission Infrared (FTIR) spectroscopy, Raman spectroscopy, Gas Chromatography Mass Spectrometry (GC-MS), and Scanning Electron Microscopy with Energy Dispersive X-ray spectroscopy (SEM-EDS). FTIR spectroscopy is used for the identification of microparticles due to being a fast and reliable technique that is non-destructive and can be used to analyse a large sample (Käppler *et al.,* 2016). However, the data interpretation from FTIR can be complex and it can be difficult to filter out background signals from particles that are of no interest. FTIR is complemented by Raman spectroscopy and more detailed readings, including pigmentations, can be generated. However, Raman spectroscopy can also lead to misidentification of contaminants, especially in a complex matrix or biological sample (Kuhar *et al.*, 2018). GC-MS does allow for valuable insights as the technique offers reliable and high sensitivity analysis, however, it is limited by not facilitating real-time analysis and must be used in conjunction with other analysis techniques to provide any quantitative benefit (Majchrzak *et al.,* 2018). Of the four techniques explored by Renner *et al.,* (2018), SEM-EDS appears the most suitable for waste fluid analysis and contaminant identification because high quality images and elemental composition of microscopic contaminants can be produced (Gniadek and Dąbrowska, 2019). While this technique does have the limitations of requiring expensive equipment and a lengthy sample preparation time, the advantages of detailed contaminant analysis make this a valuable technique for targeted contaminant removal. Furthermore, ultraviolent-visible spectroscopy (UV-Vis) is a widely used technique as it allows for qualitative analysis and quantitative detection of contaminants within a sample (Schwarzenbach *et al.,* 2010; Guspita and Ulianas, 2020; Guo *et al.,* 2020; Spangenberg *et al.,* 2021), therefore, this presents another option for exploring contaminant quantity within waste fluid produced during HPM processes. A UV-Vis spectrophotometer is used to perform optical spectroscopy, which is a method that investigates how matter interacts with light of ultraviolet and visible wavelengths and follows the principles of the Lambert-Beer law (Cerdà, Phansi and Ferreira, 2022). This law states that the relationship between absorbance and particle concentration within a sample is linear when the pathlength is constant and is summarised as the following equation:

$$A = Kbc$$

In this equation, A represents the absorbance, K is the molar absorption coefficient, b (cm) is the absorbance pathway, and c (mol/L) is the concentration of the absorbing material (Huang *et al.,* 2021). The value of the molar absorption coefficient depends upon the wavelength λ of the light used in the experiment and the properties of the absorbing material (Lavrik and Mulloev, 2017). A UV-Vis spectrophotometer generates a spectrograph, which indicates the absorbance values of the absorbing material, which can then be used to determine concentration of the absorbing material (Wang, Yangyong and Jing, 2005; Onchoke and Sasu, 2016). It is difficult to determine the composition of contaminants using only UV-Vis, therefore, this technique is best used in combination with the previously mentioned techniques, listed by Renner *et al.,* (2018), as this would generate a complete qualitative and quantitative understanding of contaminants within a sample.

Lastly, Dynamic Light Scattering (DLS) is used for contamination analysis within waste fluid, the technique is used to determine the hydrodynamic size distributions of the contaminants and generate a graph that shows particle size by intensity (e.g., Mekhamer and Al-Tamimi, 2019). The height of the peaks on the graph indicate which particle size is of greatest abundance within the sample (Mikac *et al.*, 2019). A Zetasizer is required to perform DLS, which presents the opportunity to determine zeta-potential of contaminants. This is a useful reading that indicates if the contaminant is likely to sediment or be suspended within the fluid. Generally, particles with a zeta-potential less than -20mV or greater than +20mV are considered stable, so they do not sediment within the fluid (Mikac *et al.*, 2021). Combining any of these aforementioned techniques gives valuable insights into contamination levels within waste fluid and would assist HPM companies better understand their waste composition.

2.6 Waste Re-use

When disposing of waste from grinding and EDM processes, it is important to consider two concepts: the Waste Hierarchy Index and Circular Economy. Combining these two ideas would replace the 'end-of-life' concept of a material with the possibility of finding re-use opportunities that reduces waste outputs by turning waste products into primary resources, reducing requirements for new material, and limiting overall waste creation (Ness and Xing, 2017; Kirchherr, Reike and Hekkert, 2017). Waste materials that can be readily re-used with little energy requirement and limited amounts going to landfill have higher value in the Waste Hierarchy Index, this increases the opportunities for them to be part of a circular economy (Pires and Martinho, 2019). For example, it is possible for waste grinding wheels to be repurposed into an abrasive grain for abrasive water jet machining processes (Sabarinathan *et al.*, 2019; Sabarinathan, Annamalai and Rajkumar, 2020). In this circumstance, waste grinding wheels present a high value in the Waste Hierarchy Index because transforming waste wheels into abrasive grains would rely on crushing the waste material, which requires low amounts of energy.

Another waste material that has secondary use potential is dielectric fluid from the EDM process. This waste fluid would contain high levels of contaminants, such as the metal microparticles, but this could be removed using filtration and centrifugation methods as discussed in section 2.4. Furthermore, hydrocarbon oil-based dielectric fluids contain paraffin oils, which pose an environmental risk if not properly treated (Devi, Ravindran and Kumar, 2016). However, the paraffin oils also have high potential for secondary applications, such as cosmetic products, candles, and agriculture (Petry *et al.*, 2017; Baliota and Athanassiou, 2023). If the paraffin oil could be successfully extracted in a low-cost way, then there is potential to increase profits for manufacturing companies while also reducing the environmental risk of dielectric fluid waste. To ensure the paraffin oil would be appropriate for these purposes, the chemical composition of dielectric waste must be compared with commercial paraffin oil. Gas Chromatography Mass Spectrometry (GC-MS) is used within the pharmaceutical industry for quality control due to being cost-effective and capable of inspecting high quantities at a time (Giménez-Campillo *et al.*, 2021), these qualities make GC-MS a viable technique for dielectric fluid and paraffin oil comparisons.

2.7 Summary

To meet the Net Zero targets that have been set by the UK government, high precision manufacturing (HPM) companies must find ways of reducing their carbon emissions across each scope of their business. For instance, excessive resource use and waste production during subtractive manufacturing (SM) can be a large contributor to a company's carbon footprint. Grinding and electrical discharge machining (EDM) are two of the most used SM processes in HPM, therefore, the waste generated from these processes must be reduced for HPM companies to operate sustainably. Human error and behavioural variations between employees can increase waste production during the manufacturing process, this could be a particular issue during the grinding process where operators must judge when to change a grinding wheel. Therefore, it is important to establish how grinding machine operators behave when performing this task and to determine their level of understanding surrounding sustainable manufacturing practices. Furthermore, EDM often utilises hydrocarbon oil-based dielectric fluids, which present risks for the environment unless correctly treated before disposal. Heavy metals within waste fluid are of particular concern for HPM companies due to metal ions being removed from products during EDM, but there is potential to extract these from the waste dielectric fluid through physical separation techniques like filtration and centrifugation. Additionally, it is important to understand the composition of contaminants within dielectric waste to improve waste management for HPM companies. If contaminants can be removed from dielectric fluid waste HPM companies may be able to extend the lifespan of dielectric fluid and optimise their resource use. There is potential for extracted contaminants to be sold as a by-product, contributing to a circular economy. Some of the most promising techniques for achieving complete categorisation of EDM contaminants include: Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (SEM-EDS), Dynamic Light Scattering (DLS), Ultraviolet-Visible Spectroscopy (UV-Vis), and Gas Chromatography Mass Spectrometry (GC-MS).

3.0 AIMS AND OBJECTIVES

The aim of this research is to evaluate how a small- to medium-sized enterprise (SME) in the UK's high precision manufacturing (HPM) sector can meet their sustainability and carbon targets by improving operations and processes, using ELE Advanced Technologies as the case study.

This shall be achieved through the completion of the following objectives.

1. To investigate and critically analyse different waste streams from HPM processes.
2. To evaluate methods for reducing pollutants and carbon through waste optimisation from HPM processes.
3. To use carbon accounting to evaluate process recommendations.

4.0 RESEARCH QUESTIONS

1. What are the environmental impacts of HPM companies?
2. How can HPM companies ensure employees display sustainable behaviour?
3. How can HPM waste contribute to a circular economy?

5.0 METHODOLOGY

This MRes will use a multiple method approach to answer the research questions being posed in section 4, a case study will be completed for a small- to medium-sized enterprise (SME) within the high precision manufacturing (HPM) sector to establish ways of minimising CO_{2eq} emissions and other pollutants, such as heavy metals. The case study company will be ELE Advanced Technologies (ELE). Case studies in previous research have provided a range of insights and produced valuable and highly relevant information for study participants that have highlighted ways to improve their sustainability (e.g., Zhou, Y. *et al.,* 2012; Ascione *et al.,* 2016; Zhang *et al.,* 2022). Therefore, a case study approach is the most appropriate for achieving the aim of this research.

5.1 Grinding investigation

To determine the feasibility of wheel re-use within the grinding process, grinding wheel usage was monitored across five types of grinding machines: CompactMaster, CamMaster, Microcut, Magerle, and Blohm. These machines were then grouped by their bore size; CompactMaster, CamMaster and Microcut machines accept wheels with a bore size of 203.2mm, while Magerle and Blohm machines accept wheels with a bore size of 127mm. Within these groupings, the diameters of new wheels being fitted to each machine varied; CompactMaster machines accept wheels up to a diameter of 610mm, CamMaster accept wheels up to a diameter of 550mm, Microcut accept wheels up to a diameter of 508mm, Magerle accept wheels up to a diameter of 450mm, and Blohm accept wheels up to a diameter of 400mm. These measurements are summarised in *table 3* and later visualised in *figure 4*.

Table 3: Wheel diameters and bore sizes accepted by different grinding machines at ELE Advanced Technologies.

Machine Type	Bore size (mm)	Wheel Max. diameter (mm)
CompactMaster	203.2	610
CamMaster		550
Microcut		508
Magerle	127	450
Blohm		400

To ensure monitoring was as accurate as possible, grinding operators completed a monitoring sheet each time a wheel change was performed (*appendices 12.1*), enabling the diameter of each new wheel to be confirmed and the time and date of each wheel change to be pin pointed. Used wheels were classified as being "spent" or "part-worn", spent wheels were deemed to have been used to their maximum potential by grinding operators whereas part-worn wheels were those that had been removed from the machine but were to be re-used. Once the wheels were removed from the machine, their remaining diameter was measured using a tape measure and the percentage difference between their remaining diameter and their advised minimum diameter was calculated. Descriptive statistics were used to quantify and chronicle wheel use by displaying the number of spent wheels that had reached their minimum diameter. This form of statistical analysis is most appropriate for this part of the research because emerging patterns can be identified from large datasets (e.g., Leal Filho *et al.*, 2020) . Using the findings from these descriptive statistics, the possibility of extending the usable lifespan of spent and part-worn grinding wheels by re-using the wheel across different types of grinding machines was explored. *Figure 4* highlights the wheel diameters and common bore sizes, demonstrating which machines each grinding wheel could be fitted on if they had an appropriate diameter remaining.

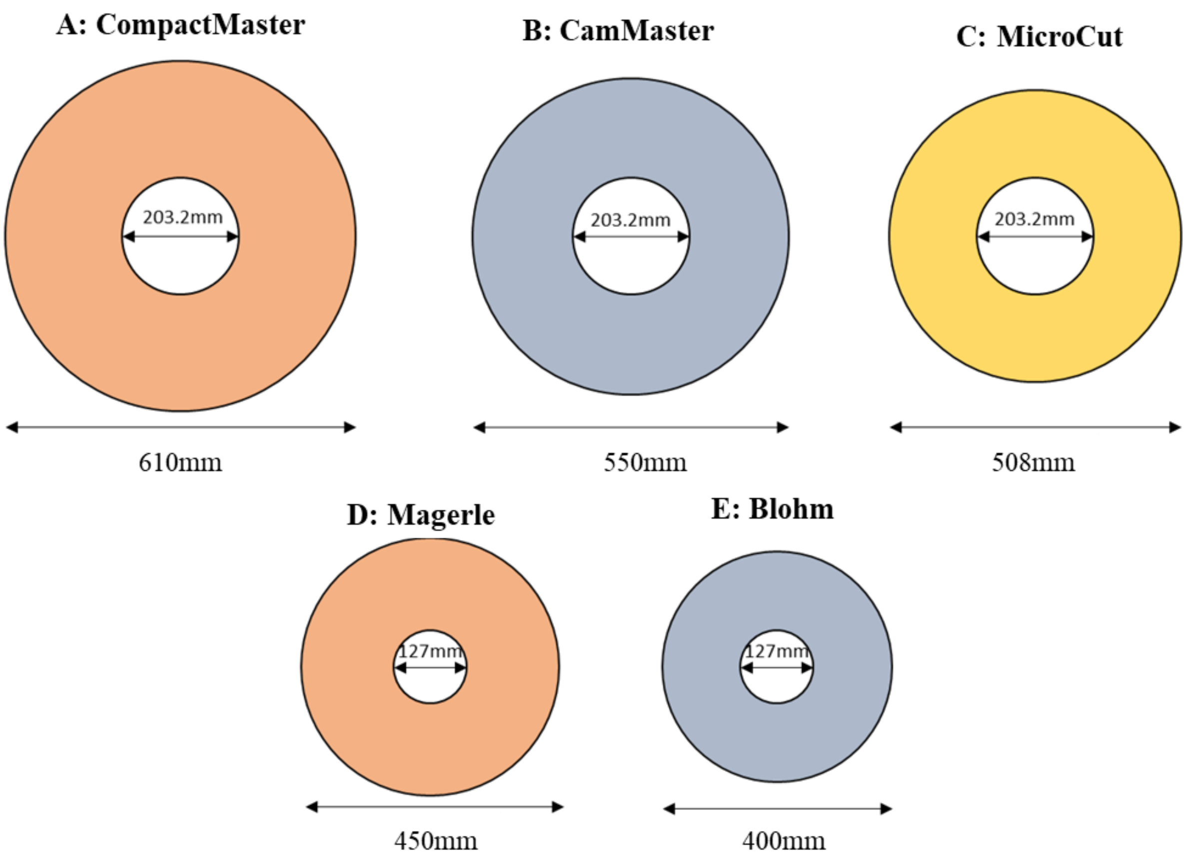

Figure 4: 1:10 ratio diagram showing diameter and bore size of five different grinding wheels. Wheel A, B, and C share a common bore diameter of 203.2cm. Wheel D and E share a bore diameter of 127cm.

Using results from wheel monitoring, the carbon impact of wheel use was determined with a simplified lifecycle assessment. The global warming potential of annual grinding wheel usage was calculated, followed by calculations of global warming potential if employees demonstrate sustainable behaviours and utilise grinding wheels until they reach their minimum diameter or re-use wheels across different grinding machines. This enabled carbon savings to be quantified. The global warming potential of grinding wheels was measured in tonnes of CO_{2eq} emissions (tCO_{2eq}). A simplified approach to LCA was most appropriate due to this paper's rationale and need to create recommendations that manufacturing companies can implement. Utilising lifecycle thinking rather than a complete LCA that meets the ISO14001 standards allow those with limited understanding of LCA to see the benefit of this paper's recommendations with greater clarity. Additionally, the purpose of this part of research is to highlight how to reduce carbon emissions through behavioural changes of grinding operators, rather than to identify the CO_{2eq} per product. Therefore, the system boundaries are largely similar and much of the LCA would become truncated. To identify any other sustainability concerns and to enable the LCA to be more comprehensive, the results from the LCA were normalised using the CML-IA method. Therefore, normalisation scores were calculated using the following reference situations: the World (1990 and 1995), Western Europe (1995) and the Netherlands (1997/1998) (Huijbregts *et al.,* 2003). This allowed the respective impacts of different environmental factors to be compared. The CML-IA method was chosen due to measuring the global warming potential while also being able to compare this against a wide range of other environmental impacts, such as 'freshwater aquatic ecotoxicity' and 'marine aquatic ecotoxicity'. Additionally, this method does not include weighting (SimaPro, 2020). The benefit of weighting being excluded is that the practitioner can apply their own judgment to the importance of each environmental impact.

To contextualise the findings from the grinding wheel monitoring and identify factors that may prevent sustainable behaviours, further research into the use of grinding wheels was conducted. Primary data was obtained from study participants using quantitative questionnaires, allowing for clear and objective findings. A questionnaire was used for this data collection as it is a fast and efficient method for collecting data from a large sample size (McGuirk and O'Neill,2010), which was required for this study due to ELE Advanced Technologies having grinding operators spread across their three sites of manufacturing. Furthermore, this part of the investigation adopted a 'factist' perspective and assumed that all information provided in these questionnaires is an accurate reflection of reality (Sandelowski, 2010). Frequency of answer selection was used to show the distribution of grinding operator responses and to visualise which responses appeared most often in the dataset. This was used in combination with cross-tabulation for inferential statistics (Byrne, 2007). Cross-tabulation was conducted in IBM SPSS Statistics and allowed relationships within the data that may not be readily apparent from survey responses to be identified and explored. Through this analysis, factors that significantly influence grinding operator behaviours were highlighted, resulting in a greater understanding of the limitations to grinding process sustainability for HPM companies (Marisamynathan and Perumal, 2014). Furthermore, all questionnaire data was viewed from the perspective of practice theory (section 2.2), to theorise how HPM companies can increase the frequency of sustainable behaviours from their employees. This behavioural theory has been applied due to being the most appropriate theory when considering internal and external factors that influence decision-making, and this theory has been successfully applied to environmental behaviour studies in the past (e.g., Hargreaves, 2011).

5.2 Electrical discharge machining investigation

A mixed-method approach using qualitative and quantitative research was conducted into contamination levels of waste dielectric fluid from the EDM process. To begin, a sample of waste dielectric fluid was required from ELE Advanced Technologies. This was extracted from a barrel of fluid that had reached the end of its usable lifespan and was set to be discarded. The fluid was mixed before being sampled to ensure all contaminants were dispersed and none had sedimented. Following this, contaminant separation studies were conducted for the removal of contaminants from the waste fluid. The first of these studies utilised a three-stage Büchner filtration experiment to pass waste dielectric through filter papers of different pore sizes; 25µm, 11µm, and 6µm. These filter papers were then dried and weighed to establish the mass removed at each stage of the Büchner filtration, allowing a size distribution to be generated for contaminants larger than 6µm, which provides important information about the waste sample (e.g., Dris *et al.*, 2015). A flow diagram of the filtration experiment is displayed in *figure 5.*

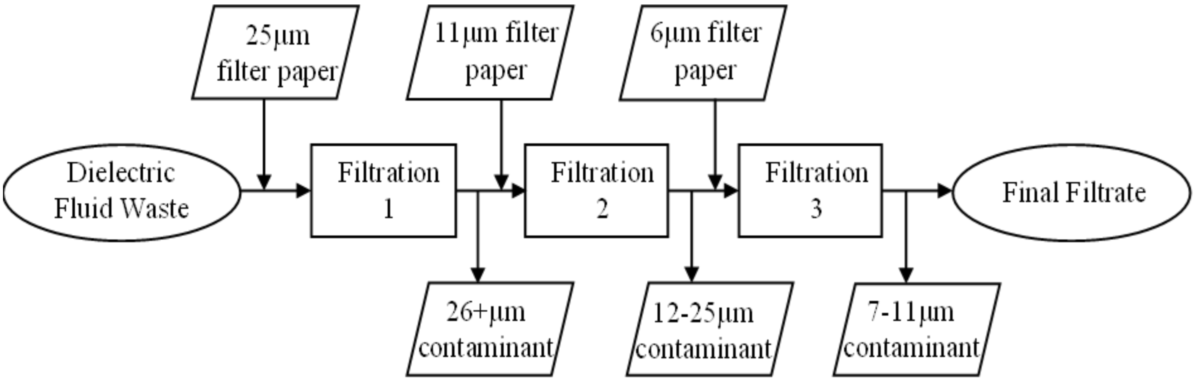

Figure 5: Flow diagram of the Büchner filtration experiment, resulting in the 'filtered' sample.

Centrifugation was used in the second separation study so that the effectiveness of this separation method could be compared against the effectiveness of filtration (e.g., Singh and Patidar, 2018). 'Untreated' dielectric fluid samples were centrifuged, allowing a point of comparison between centrifugation and filtration. 'Filtered' samples were also centrifuged so that it could be determined if the separation methods are more effective at removing contaminants when used in combination. A summary of the wet and dry samples being collected can be found in *table 4.* Filtration and centrifugation were chosen for the separation studies because they are both effective waste treatment methods that are low cost and can be conducted in limited space, therefore, they present an excellent opportunity for a HPM company that may wish to extract contaminants from their waste fluid before its disposal (Gunatilake, 2015; Hildebrandt *et al.,* 2019). Both experiments were necessary to ensure all possible contamination was removed from the waste dielectric fluid so that it could be accurately analysed.

Table 4: Summary of the wet and dry samples generated by the separation studies.

<table>
<tr><th>Separation study</th><th colspan="2">Wet samples</th><th colspan="6">Dry samples</th></tr>
<tr><td>Filtration</td><td colspan="2">‘Filtered’ sample</td><td colspan="2">7-11µm contaminants</td><td colspan="2">12 - 25µm contaminants</td><td colspan="2">26+µm contaminants</td></tr>
<tr><td>Centrifugation</td><td>‘Centrifuged’ sample</td><td>‘Filtered and centrifuged’ sample</td><td colspan="3">Pellet - Waste dielectric fluid</td><td colspan="3">Pellet - Final filtrate</td></tr>
</table>

To compare the effectiveness of filtration and centrifugation, contaminant analysis was performed, and each wet and dry sample was analysed to generate a qualitative understanding of the contaminant composition within waste dielectric fluid. First, the dry samples were analysed using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS), allowing for the elemental composition of the dielectric fluid contaminants to be identified and a high-resolution image of these contaminants to be generated. Characterisation of the contaminants is extremely important as this can identify polluting material in the waste fluid (Wagner *et al.,* 2017). Following this, quantitative UV-Vis was conducted to determine the absorbance values of wet samples. The wavelength maxima were used to identify potential contaminants remaining in the samples, which were then checked against the SEM-EDS results to confirm their presence. The absorbance values at these wavelengths allowed concentrations for identified contaminants to be calculated. UV-Vis was chosen as it is commonly used when examining contamination levels of fluids and colloids (Birdwell and Engel, 2010; Yao *et al.,* 2014; Szabo and Tuhkanen, 2016), making it a highly appropriate technique that presents valuable information regarding any remaining contamination. Samples being inspected by UV-Vis had either undergone filtration, centrifugation, or both. The absorbance values of each sample were compared using a one-way ANOVA, enabling significant differences in absorbance values to be identified (Shokouhi, Sohrabi and Mofavvaz, 2020).

Dynamic Light Scattering (DLS) was then used to determine the diameters of microparticle contaminants within the wet samples (e.g., Mekhamer and Al-Tamimi, 2019). This was a valuable measurement to take because the effectiveness of filtration and centrifugation for the removal of the smallest microparticles could be compared. Lastly, Gas Chromatography Mass Spectrometry (GC-MS) was used to identify the hydrocarbon structures within dielectric fluid waste and compare these structures across wet samples. This analytical technique was very important because a breakdown of hydrocarbons could impact the performance of dielectric fluid in the EDM process (Dhakar *et al.*, 2022). Combining these analytical techniques allowed for detailed understanding of contaminants within the waste dielectric fluid, which is a highly important step in making sure polluting microparticles in EDM waste can be reduced.

6.0 STUDY CHAPTER 1: GRINDING

This study chapter explores ways of reducing CO_{2eq} emissions from a HPM company's grinding process. Therefore, the efficiency of resource use within the grinding process and factors limiting sustainable behaviour in grinding operators were investigated.

6.1 Methods

6.1.1 Wheel monitoring

Grinding wheel monitoring took place over a three-month period, between 1st January 2023 to 31st March 2023, across five different types of grinding machine: CompactMaster, CamMaster, Microcut, Magerle, and Blohm. Grinding wheels were used as normal by the operators before being removed once they were no longer required or they were deemed unfit for purpose. Wheels were classified as 'spent' or 'part-worn'. Spent wheels were those that were to be disposed of, part-worn wheels were those that were to be re-used by operators.

Diameter measurements from the spent and part-worn wheels were taken on the last day of each month, January, February, and March. Three measurements of the wheel's diameter were taken using a tape measure, allowing an accurate measurement for the average remaining diameter of each spent and part-worn wheel. This average remaining diameter was determined with a ±1mm certainty. The remaining usable diameter was calculated by subtracting the minimum diameter of each wheel from the average remaining diameter and the total number of wheels that achieved their minimum diameter was recorded. This was not possible for CompactMaster wheels due to the minimum diameter being unknown.

Total weight of grinding wheel use was calculated using the average weight of each type of wheel used during the monitoring period. The wheel manufacturer and pre-use wheel dimensions were used to define the type of wheel. Five unused wheels of each type were weighed, and the average weight was recorded. This weight was multiplied by the number of wheels used during the monitoring period to obtain an accurate measurement for the total weight of grinding wheel use.

6.1.2 Environmental impact

The environmental impact of grinding wheel use over a one-year period has been calculated using a simple, cradle-to-gate lifecycle assessment (LCA), which was built using secondary data from SimaPro software. A cradle-to-gate assessment is vital for understanding environmental impacts of a product, which can influence how a product is used (e.g., Laveglia *et al.*, 2023). The "Ecoinvent 3 – allocation, cut-off by classification – system" database and "CML-IA baseline V3.07 / EU25" method were used to model grinding wheel impacts.

The primary impact category considered for this part of the study was 'Global Warming Potential (GWP)', which is defined as: The warming influence in relation to that of CO_2 over a 100 year period (UK Department for Business, Energy, and Industrial Strategy, 2020). Results obtained from the LCA were normalised to identify any other impact categorises of concern. Additionally, the LCA incorporated the following assumptions:

1. Grinding wheel use remains consistent over a one-year period.
2. Each grinding wheel was manufactured using the same steps.
    a. *Material mixing*: Aluminium oxide (alumina; Al_2O_3) and bonding materials mixed to form basis of the wheel.
    b. *Wheel moulding and firing*: Material mixture then shaped in a mould and given circular central hole. Moulded wheel then pressed and heated to solidify the mixture.
    c. *Wheel finishing*: The wheel is shaped to meet specific requirements e.g., bore size, diameter, and circumference.
3. Part-worn wheels grind as effectively as new wheels.

The environmental impact of current wheel use was then compared against two alternate scenarios in which grinding operators displayed more sustainable behaviour during the wheel change. These scenarios are described below.

Scenario A: *Grinding wheels are used for their maximum lifespan, so all wheels achieve their minimum diameter.*

Scenario B: *Spent grinding wheels are used in place of new wheels across different grinding machines.*

6.1.3 Questionnaire

The questionnaire contained 27 multiple choice questions and was structured into three sections. Section one asked five questions to gather information that allowed grinding operators to be sorted into groups, based on their site of operation, length of employment, and types of grinding machine they operate. Sections two included 16 multiple choice questions that assessed grinding operator behaviour and grinding wheel use. Lastly, the sustainability awareness of each participant was assessed in section three, which contained six questions regarding employee sustainability training and barriers to sustainable grinding. The questionnaire is available in appendices 12.6.

The questionnaire was developed using the survey software, Qualtrics. All grinding operators were provided with a questionnaire, totalling to 32 questionnaire recipients. A link to the questionnaire was distributed to all participants via email from their human resources department to ensure anonymity. Participants were required to consent to take part in the investigation, with the option of withdrawing from the questionnaire and ability to skip any questions they did not wish to answer. Only one questionnaire was completed per participant.

6.2 Results and Analysis

6.2.1 Wheel monitoring

Diameter and weight measurements were obtained from a total of 81 grinding wheels, 73 wheels were categorised as ‘spent’ and 8 wheels were categorised as ‘part-worn’. All 8 part-worn wheels were obtained from CompactMaster because no other machine had an area to store part-worn grinding wheels. For spent wheels, 9 were from CompactMaster, 23 were from CamMaster, 15 were from Microcut, 12 were from Magerle, and 13 were from Blohm. Out of the 63 spent wheels across

CamMaster, Microcut, Magerle, and Blohm machines, only 7 wheels achieved their minimum diameter; 2 from Microcut and 5 from Blohm. Therefore, only 11.11% of all wheels achieved their minimum diameter. A summary of the diameter measurements taken from the wheels is found in *table 5*.

Table 5: Summary of the wheels used and remaining diameters across each grinding machine.

Machine	**Wheels recorded**	**Average remaining diameter (mm)**	**Standard deviation (± mm)**	**Average usable diameter remaining (%)**	**Wheels reaching min. diameter**
CompactMaster (Part-worn)	8	548.54	10.45	N/A	N/A
CompactMaster (Spent)	9	460.04	11.65	N/A	N/A
CamMaster (Spent)	23	447.88	14.11	8.59	0
Microcut (Spent)	15	398.42	16.39	5.26	2
Magerle (Spent)	12	311.19	33.94	14.18	0
Blohm (Spent)	13	268.17	16.42	3.09	5

Furthermore, 11 different types of grinding wheel were used across all grinding machines: one on CompactMaster, two on CamMaster, three on Microcut, three on Magerle, and two on Blohm. In total, 1641.13kg of spent grinding wheels were used during the three-month monitoring period: 310.32kg by CompactMaster, 815.40kg by CamMaster, 198.70kg by Microcut, 133.89kg by Magerle, and 182.82kg by Blohm. The breakdown of wheel usage and weights can be found in *table 6.*

Table 6: Summary of wheel types used across each different grinding machine. The number of wheels used on each machine is shown, along with the average weight of each wheel before they are used for grinding.

Machine	**Manufacturer**	**Dimensions (mm)**	**Average weight (kg)**	**3-month wheel use**	**Total weight (kg)**
CompactMaster (Part-worn)	Tyrolit UK Ltd	610x89x203.2	34.48	8	275.84
CompactMaster (Spent)	Tyrolit UK Ltd	610x89x203.2	34.48	9	310.32
CamMaster	Tyrolit UK Ltd	550x120x203.2	39.70	13	516.10
	Saint-Gobain Abrasives Limited	550x89x203.2	29.93	10	299.30
Microcut	Tyrolit UK Ltd	508x20x203.2	7.81	1	7.81
		508x50x203.2	10.71	5	53.55
		508x100x203.2	15.26	9	137.34
Magerle	Tyrolit UK Ltd	450x30x127	6.54	2	13.08
		450x50x127	11.40	7	79.80
	Saint-Gobain Abrasives Limited	450x55x127	13.67	3	41.01
Blohm	Tyrolit UK Ltd	400x65x127	13.40	11	147.40
		400x100x127	17.71	2	35.42

6.2.2 Environmental impact

As displayed in *table 6*, an approximate 1641.13kg of grinding wheels were used across all machines during the three-month monitoring period. This is based on spent wheels only, due to part-worn wheels not being discarded during the monitoring period. Therefore, it is predicted that 6564.52kg of grinding wheels are used annually. By using the 6564.52kg estimation in the LCA, the carbon equivalence of grinding wheel use over one year was calculated as 31.9tCO_{2eq}. All areas of CO_{2eq} emissions are displayed in *figure 6*.

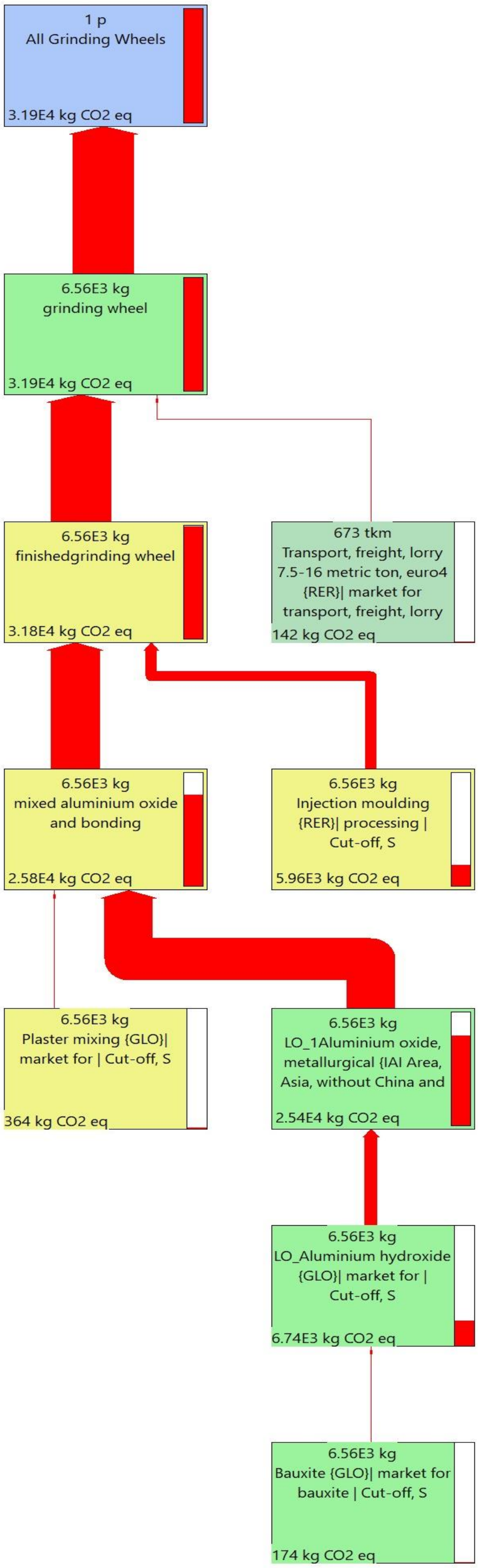

Figure 6: Network tree displaying CO_{2eq} emissions associated with alumina grinding wheel manufacturing and transport.

Normalisation of environmental impacts using the CML-IA method highlighted the long-term ‘freshwater aquatic ecotoxicity’ and ‘marine aquatic ecotoxicity’ impacts as greater concerns than the ‘global warming potential’ of grinding wheels, likely due to the water requirements of grinding wheel manufacturing. The normalised graph is displayed in *figure* 7.

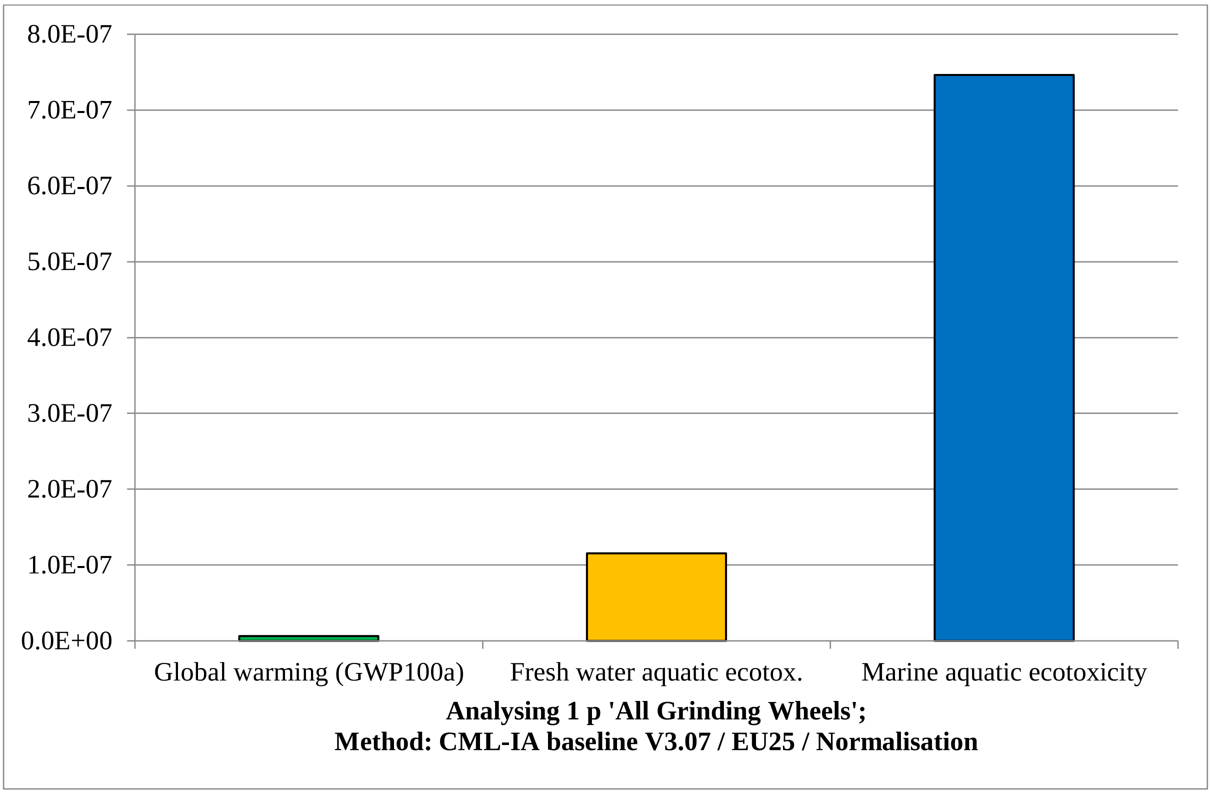

Figure 7: Comparative impact of grinding wheels across three environmental factors: global warming potential, fresh-water aquatic ecotoxicity, and marine aquatic ecotoxicity. Graph based on current grinding wheel usage.

Based on current grinding wheel usage (*6564.52kg per year*), 5510 m^3 of water is required to manufacturer enough wheels to meet this demand. This is equivalent to 5,510,000 litres of water per year. A breakdown of the current water requirements for each stage of grinding wheel manufacturing is shown by the network tree in *figure 8* below.

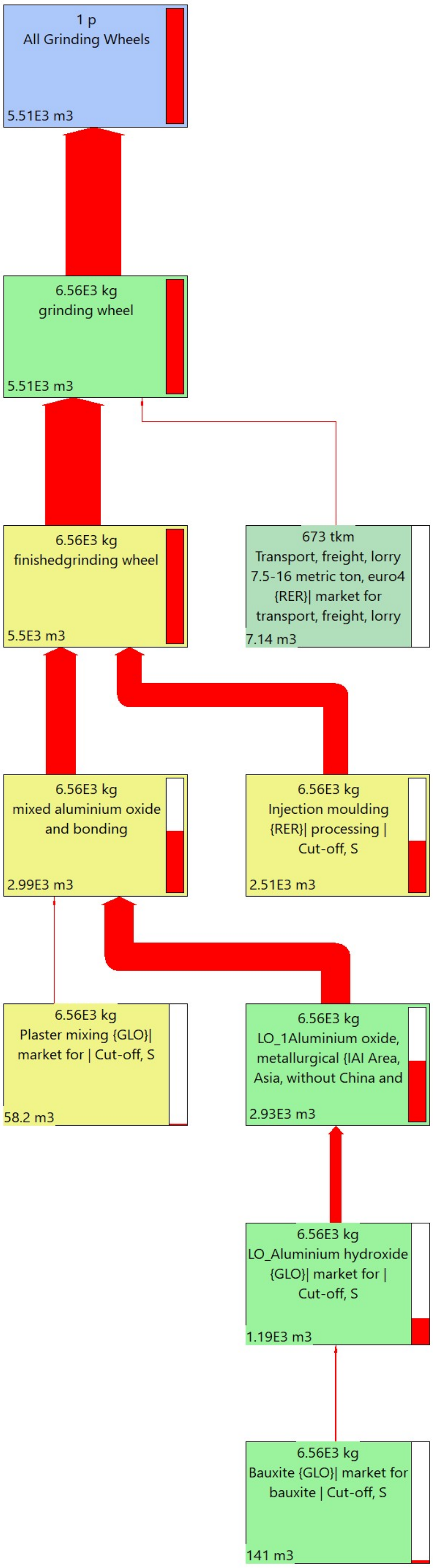

Figure 8: Network tree displaying water usage associated with alumina grinding wheel manufacturing and transport.

6.2.2.1 Scenario A

This scenario calculates the reduction in CO_{2eq} emissions and water usage if all grinding operators used wheels to their minimum diameters. CompactMaster wheel measurements are excluded from this scenario, due to the minimum diameter of these wheels being unknown.

To predict the number of wheels that could be saved for each machine over one year, the percentage usable diameters of wheels from each machine (*table 5*) were used. For example, the average spent CamMaster wheel was 8.59% away from its minimum diameter. Therefore, one wheel could be saved for every 11.64 wheels [12 whole wheels] that are used to their minimum diameter. Using the results in *table 6*, the average weight per CamMaster wheel was 35.45kg (*815.40kg / 23 wheels*). Based on the 23 wheels used during the three-month monitoring period, a prediction of 92 wheels being required annually was made. If all these wheels are used to their minimum diameter, 7.67 [7 whole] wheels could be saved per year. In total, the weight of grinding wheel usage could be reduced by 248.17kg.

Continuing this for the remaining machines showed that one Microcut wheel can be saved for every 19.01 [20 whole] wheels, one Magerle wheel can be saved for every 7.05 [8 whole] wheels, and one Blohm wheel can be saved for every 32.34 [33 whole] wheels that are used to their minimum diameter. Therefore, three Microcut wheels, six Magerle wheels, and one Blohm wheel could be saved each year. This results in 39.74kg, 66.95kg, and 14.06kg of grinding wheel savings respectively.

Overall, 368.91kg of grinding wheels could be saved annually by using wheels to their minimum diameter, resulting in an annual grinding wheel usage of 6195.61kg. To determine the carbon and water savings caused by this scenario, the new predicted grinding wheel usage was used in the lifecycle assessments. This output 30.1 tCO_{2eq}, identifying a carbon saving of 1.8tCO_{2eq} and displayed an annual water usage required of 5,200,000L, identifying a water saving of 310,000L.

6.2.2.2 Scenario B

This scenario calculates the reduction in CO_{2eq} emissions and water usage that could be achieved if grinding operators used spent grinding wheels from one machine as a part-worn grinding wheel for another machine. Spent wheels can only be used between machines that accept wheels of the same bore size. As shown in *figure 4*, CompactMaster, CamMaster, and Microcut accept wheels with a bore size of 203.2mm, while Magerle and Blohm accept wheels with a bore size of 127mm.

The percentage usable diameter required to be considered a part-worn wheel was determined by calculating the percentage difference between the average diameter of spent CompactMaster wheels and part-worn CompactMaster wheels. The average diameter of spent CompactMaster wheels was used as the minimum diameter in this calculation, due to the official minimum diameter being unknown. Therefore, the percentage usable diameter required to be considered a part-worn wheel was found to be 17.55%. This was rounded up to 18% when calculating the diameter for part-worn wheels from other grinding machines to account for redressing of the wheel. The range of diameters required for a wheel to be considered part-worn across each type of grinding machine is displayed in *table* 7.

Table 7: Part-worn ranges for each grinding machine.

Machine	Min. diameter (mm)	Max. diameter (mm)	Min. part-worn diameter (mm)	Part-worn range (mm)
CompactMaster	460.04	610	548.54	548.54 – 610
CamMaster	411	550	484.98	484.98 – 550
Microcut	378	508	446.04	446.04 – 508
Magerle	270	450	318.6	318.60 – 450
Blohm	260	400	306.8	306.80 – 400

During the three-month monitoring period, 8 spent CompactMaster and 12 spent CamMaster wheels had a remaining diameter within the part-worn range for Microcut. Also, 3 spent Magerle wheels had a remaining diameter within the part-worn range for Blohm. If scenario B was followed and these wheels were fitted to their appropriate machines instead of a new grinding wheel, 20 Microcut wheels and 3 Blohm wheels could have been saved over 3-months. Therefore, an estimated 80 Microcut wheels and 12 Blohm wheels could be saved if scenario B is followed over a one-year period. This would reduce wheel use by a total of 1228.49kg, 1059.73kg from Microcut and 168.76kg from Blohm.

To determine the carbon and water savings caused by this scenario, the new predicted grinding wheel usage of 5336.03kg was used in the LCAs. This resulted in an output of 25.9 tCO_{2eq}, identifying a carbon saving of 6.0 tCO_{2eq}. Additionally, 4,480,000L of water was required annually, identifying a saving of 1,030,000L.

6.2.3 Questionnaire

All 32 grinding operators received the questionnaire, with 19 being completed and returned. From the returned questionnaires, factors influencing operator behaviours were identified. Respondents chose from provided options without a limit to how many options could be selected. The importance of each factor to grinding operators has been determined based on selection frequency. Results from the questionnaire are summarised in table 8, with a breakdown of results being located in appendices 12.2.

Table 8: Grinding operator questionnaire responses. Reason's for changing a grinding wheel, beliefs regarding part-worn grinding wheel storage and re-use, and barriers to a sustainable grinding process.

Questions							
Reasons for changing a grinding wheel.	**Selection frequency (%)**	**Barriers to storing part-worn wheels.**	**Selection frequency (%)**	**Barriers to using part-worn wheels.**	**Selection frequency (%)**	**Barriers to a sustainable grinding process.**	**Selection frequency (%)**
The minimum diameter of the grinding wheel has been reached.	76.47	There is no re-use pile.	82.35	There is no re-use pile	82.35	Insufficient sustainability training	64.71
The next job requires a different type/size of grinding wheel.	70.59	The wheel has reached its minimum diameter.	64.71	They would require measuring before use.	58.82	Viable grinding wheels being wasted.	58.82
Job has been completed.	58.82	The wheel is close to its minimum diameter.	41.18	There are no barriers to using a wheel from the re-use pile.	17.65	Energy waste from inefficient machines.	35.29

From the cross-tabulation analysis of the questionnaire, correlations between answers became apparent. *Figure 9* summarises the correlations identified from cross-tabulation analysis, which are further explained in appendices 12.3.

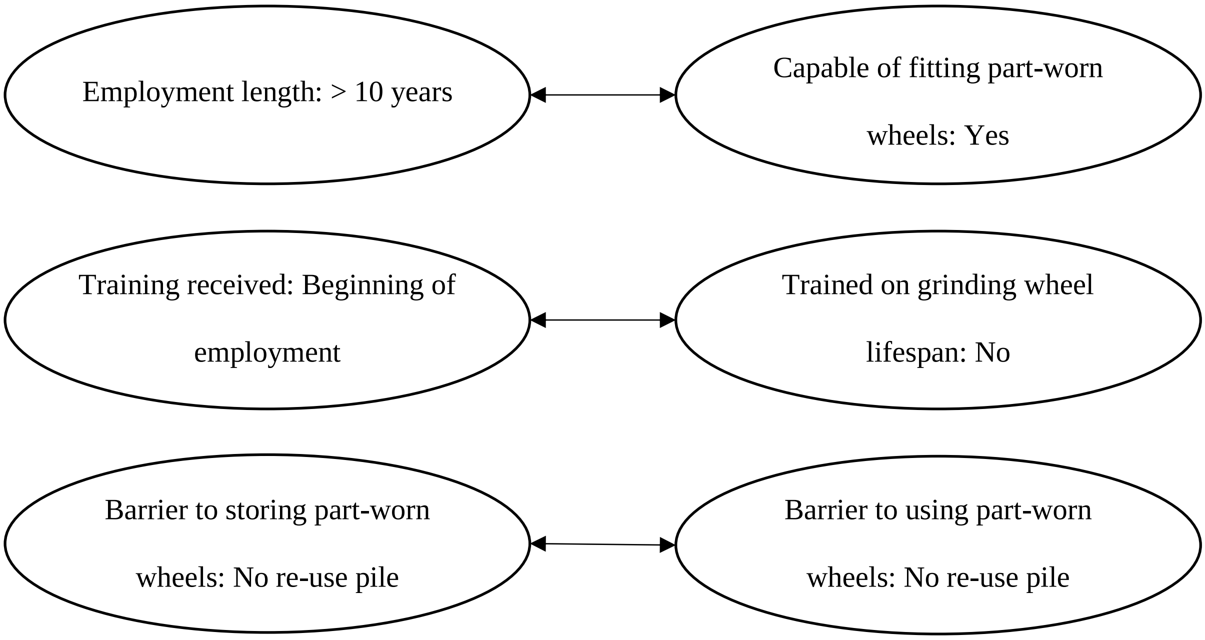

Figure 9: Correlations between questionnaire answers, identified by cross-tabulation analysis.

6.3 Chapter Summary

Throughout this study chapter the environmental impact of the grinding wheels has been analysed, with two different wheel use scenarios being presented and an exploration of factors affecting operator behaviours being conducted. From this research it becomes clear that inefficient resource use negatively impacts the carbon footprint and sustainability of the grinding process and that provisions should be put in place that enable operators to display more sustainable behaviours.

Only 11.11% of grinding wheels were used to their minimum diameter, causing a significant number of viable grinding wheels to be wasted and 31.9 tCO_{2eq} emissions to be generated annually. Theoretically, using all wheels to their minimum diameter before removing them from the grinding machine, as described in scenario A, could save 1. 8 tCO_{2eq} per year. However, using a spent wheel from one machine as a part-worn wheel for another, as described in scenario B, shows greater potential for carbon savings because 6.0 tCO_{2eq} could be saved annually if this action is taken. Interestingly, the global warming potential of grinding wheel waste is not the only cause for concern when considering the sustainability of grinding. The level of risk posed by freshwater and marine pollution is shown to be of even greater significance, possibly due to the high level of water requirement for grinding wheel manufacturing. Manufacturing enough grinding wheels to fulfil the current 6564.52kg annual use requires 5,510,000 litres of water. This water requirement is reduced to 5,200,000 litres if scenario A is implemented, or to 4,480,000 litres if scenario B is followed. Therefore, reducing wheel waste is important for reducing air and water pollution, which increases the environmental sustainability of the manufacturing company. Following the framework laid out by either scenario A or scenario B would improve the environmental sustainability of the grinding process.

However, the questionnaire highlighted some of the challenges that must be overcome before either scenario can be implemented. It was found that the main reason for operators changing a grinding wheel is the belief that it has reached its minimum diameter, suggesting that each operator believes they have used the wheel for its maximum lifespan. This is interesting because very few grinding wheels actually achieved their minimum diameter, with large standard deviations around the mean diameters from each machine. This indicates that grinding operators use their own judgement to decide when the minimum diameter has been reached, and that this is inconsistent between operators, leading to the high variation. Therefore, grinding operators should receive training and guidance regarding what the minimum diameter is for wheels from each machine. This would improve consistency in grinding wheel changes and increase the probability a wheel is used to its minimum diameter, because all operators would be working towards a standard measurement. Despite most operators claiming that the wheel reaching its minimum diameter is their main reason for performing a wheel change, they also believe that the second biggest barrier to a sustainable grinding process is viable grinding wheels being wasted. While it is possible that this is due to social-desirability bias and questionnaire respondents wanting to select a favourable reply, this may be another indication of variation in operator judgment regarding minimum wheel diameters. Each operator seems to think they are achieving the minimum diameter, but viable wheels are still being wasted, implying that they believe other operators are not getting the maximum potential from each wheel and are causing the excessive wheel waste. This further highlights the need for operator training that explains each wheel’s minimum diameter, to ensure that all operators are working towards the same standard measurements and are using grinding wheels more sustainably.

Additionally, according to grinding operators, the biggest barrier to a sustainable grinding process is the lack of sustainability training. Therefore, it is vital that this form of training is provided and that the manufacturing company is able to communicate the importance of sustainability to their employees. This training would benefit from including details about actions and behaviours operators must display to make the grinding process more sustainable, such as using grinding wheels as described in scenario A or scenario B. The training should be kept updated and delivered regularly to ensure long-term employees remain aware about the importance of sustainable grinding and how they can assist with its implementation. This belief is supported by the correlation between operators who only received training at the beginning of their employment and operators who haven't been trained on the usable lifespan of a grinding wheel. Therefore, even if this vital information is covered in the training sessions it is possible that operators do not remember being taught it. This could suggest that the frequency of training should be increased to ensure that operators remain up to date on how to make the grinding process sustainable. One topic that could be covered in the sustainability training is how to re-use part-worn grinding wheels, because this was shown to reduce the carbon footprint of the grinding process in scenario B. This would require storing the part-worn wheels until they can be re-used on another grinding machine. However, this is hindered by the lack of a designated area to store part-worn wheels, as displayed by operators voting the lack of a re-use pile as the biggest barrier to storing and re-using part-worn wheels. This lack of provision for part-worn wheel re-use limits the number of wheels that can be used for their maximum lifespan and leads to large amounts of viable grinding wheels being wasted, hindering the sustainability of the grinding process.

When considering operator behaviour from the perspective of Social Practice Theory (SPT), discussed in section 2.2 of the literature review, it is likely that the lack of provision for a sustainable grinding process is a major contributor towards inefficient resource use. SPT suggests that an individual's behaviour is adaptable and their views about what is important can change when new information is presented. This allows individuals to display new behaviours when opportunities become present within their environment. From this perspective, operators' beliefs reflect the culture of the company, and their behaviours are dependent on the opportunities provided to them. The lack of appropriate training prevents the required culture for sustainability being created, due to operators lacking crucial information to make an informed decision. Additionally, the means for re-using part-worn wheels are not provided due to the lack of a re-use pile. Therefore, operator's do not display sustainable behaviours and their actions lead to higher wheel waste and CO_{2eq} emissions. If a re-use pile and suitable training were in place then operator behaviours would likely reflect improved sustainability, allowing resources to be used efficiently and the carbon footprint of the grinding process to be reduced.

Overall, a push for all grinding wheels to be used for their maximum lifespan, either through re-use of part-worn wheels or replacing them only when they have reached their minimum diameter, would increase the sustainability of a high precision manufacturing company. If operators adapt how they use grinding wheels, progress towards achieving Net Zero targets can be made for the manufacturer. However, this is only possible if the correct provisions are in place from the company to begin with. Frequent training is required as well as a greater focus on sustainability during these training sessions. Additionally, a designated space to store part-worn grinding wheels is essential for their re-use. Without these provisions, viable part-worn wheels are wasted as there is no other option but to dispose of them.

6.4 Limitations

Engagement with the questionnaire did not achieve the desired levels, meaning that significance of patterns identified during descriptive statistical analysis was difficult to clarify. However, 59.38% of all operators completing the questionnaire does provide useful insights into the views of the entire population. It is also acknowledged that the carbon footprints calculations did require assumptions. However, these assumptions are clearly stated, and the accuracy of these calculations were maximised by taking a large number of measurements over a substantial monitoring period. Lastly, the country of origin for water used within the manufacturing of grinding wheels has not been noted. This was due to not having the complete background of where the manufacturing materials originated. While this does not greatly impact this research, future studies should consider this because the amount of water being used has varying impacts on pollution and water scarcity depending on country of origin.

7.0 STUDY CHAPTER 2: ELECTRICAL DISCHARGE MACHINING

The purpose of this study chapter is to identify ways that the EDM process can be made more environmentally sustainable. Therefore, methods of cleaning waste dielectric fluid so that it can be re-used in the EDM process were explored, and ways of reducing polluting risk of dielectric fluid waste by identifying and removing contaminating microparticles were investigated. 1 litre of clean dielectric fluid was provided by ELE Advanced Technologies and 5 litres of waste dielectric fluid were sampled as described in section 5.2. The brand of dielectric fluid provided was PrimaSpark.

7.1 Methods

Six different experiments were conducted for the purpose of separating and identifying the contaminating microparticles within the waste dielectric fluid. To separate the microparticles from the fluid, filtration and centrifugation were used (Dris et al., 2015; Singh and Patidar, 2018). Once the microparticles were separated, SEM-EDS was used in combination with UV-Vis to identify the elemental composition of these contaminants, both of these methods are effective for the detection and identification of pollutants (e.g., Kaur, Singh and Singh, 2020; Longoria-Rodríguez et al., 2021). These methods have been used in combination for a similar purpose by Konan *et al* (2017). DLS was performed to examine the effectiveness of filtration and centrifugation at cleaning the waste fluid (Mekhamer and Al-Tamimi, 2019). GC-MS was also performed to check if the contaminant separation methods impact the hydrocarbon structures of the fluid (Dhakar et al., 2022). Contaminant separation methods are found in sections 7.1.1 and 7.1.2. Contaminant analysis methods are found in sections 7.1.3, 7.1.4, 7.1.5, and 7.1.6.

7.1.1 Filtration

Filtration required a Büchner funnel and Whatman grade 1, 3, and 4 filter papers of pore sizes 11µm, 6µm, and 25µm respectively. 3 litres of 'untreated' dielectric fluid was filtered using a series of three Büchner filtration experiments (*figure 5*). First, the 'untreated' fluid was filtered through the Whatman grade 4, 25µm pore size filter paper. This filtrate was then filtered through the Whatman grade 1, 11µm pore size filter paper. The second filtrate was filtered through the Whatman grade 3, 6μm pore size filter paper. The final filtrate was then stored as the 'filtered' sample to be used later in the study. Two filter papers were required to complete the second and third filtration due to pores becoming clogged by the contaminants within the fluid sample. Each filter paper was collected after use and debris was weighed before and after being dried in a 110°C oven for 24 hours. This experiment was also conducted using 3 litres of 'clean' sample for a control.

7.1.2 Centrifugation

Centrifugation was used for the extraction of contaminant particles from 'untreated' and 'filtered' dielectric fluid samples. 3x50ml samples of 'untreated' and 'filtered' fluid were used, and differential pelleting centrifugation was performed for 60 minutes at 14000 RPM. This produced condensed pellets of contaminants, which were then extracted and dried in an oven for 48 hours at 110°C to ensure no moisture remained. The supernatant from the 'untreated' sample was collected and stored as 'centrifuged' sample for further analysis. The supernatant from the 'filtered' sample was also collected and stored as 'filtered and centrifuged' sample for later use. For the control, 3x50ml of 'clean' fluid also underwent the centrifugation experiment.

7.1.3 Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy

A Thermo Scientific Quattro ESEM was required for SEM and EDS analyses. Acceleration voltage was set at 30kV and area analysis was conducted for EDS. Dried filter papers from the filtration experiment were cut into $10cm^2$ sections, with one section for each filter paper (11μm, 6μm, and 25μm pore sizes) being placed onto separate carbon carriers and stuck down with carbon tape, totaling to three samples. This was conducted for each paper that had been used to filter the 'untreated' sample as well as the 'clean' sample, to act as the control.

This analysis was also conducted on dry samples obtained from the centrifugation of 'untreated' dielectric fluid. However, this could not be conducted for the control group, because no contaminants could be separated from the 'clean' sample using centrifugation. In total, three dry samples were analysed from 'untreated' dielectric fluid.

7.1.4 Ultraviolet-Visible Spectroscopy

A Lightwave II 7120 V1.2 Spectrophotometer was used to perform UV-Vis on dielectric fluid samples. Samples were placed into a quartz cuvette that had a 1cm diameter. 3ml of deionized water was used to set the baseline across a 200-900nm wavelength range. The 'untreated' sample was diluted in a 1:1 ratio with 'clean' sample, to prevent the absorption value exceeding the 2.5A limit of the Spectrophotometer. Once the baseline was set, 3x3ml samples of 'untreated (diluted)', 'filtered', 'centrifuged', 'filtered and centrifuged', and 'clean' dielectric fluid were ran.

7.1.5 Dynamic Light Scattering

'Untreated', 'filtered', 'centrifuged', 'filtered and centrifuged', and 'clean' samples were vortexed for 30 seconds to disperse all microparticle contaminants within the matrix. 1ml was extracted from each sample and transferred into a polystyrene latex cuvette. DLS was performed using a Malvern Zetasizer, with three readings taken per sample.

7.1.6 Gas Chromatography Mass Spectrometry

200 µl of dielectric fluid and 1ml of n-hexane were diluted to make the samples for GC-MS testing. This was performed for each of the dielectric fluid samples; 'clean', 'untreated', 'filtered', 'centrifuged', and 'filtered and centrifuged'. 1µl of the prepared samples were required for the analysis. The experiment was conducted using the ThermoFisher Trace 1300 Gas Chromatograph and the ThermoFisher ISQ LT Single Quadrupole Mass Spectrometer. Column type 5MS was used, with dimensions of 30m length, 0.25mm diameter, and 0.25µm thickness. Inlet temperature was set to 280^{o}C, the column temperature was maintained at 60 ^{o}C for 1 minute, then increased to 250 ^{o}C at a rate of 5 ^{o}C min^{-1} and maintained for 1 minute, before being increased to 280 ^{o}C at the rate of 10 ^{o}C min^{-1} and maintained for 5 minutes. The speed of fluid passing through the column was set to 1ml min^{-1}, with helium (He) being used as the carrier gas. 100:1 was the by-pass flow proportion, and the transfer line

temperature was set to 280^{o}C. Compounds within the solvent were detected with a 50-600 amu scanning method. Voltage of the detector was set to 1.01kV.

7.2 Results and Analysis

Data obtained from contaminant separation and contaminant analysis methods is displayed and analysed in section 7.2.1 to 7.2.6. The total weight of contaminating microparticles extracted during filtration and centrifugation are shown, along with the elemental composition of the microparticles from SEM-EDS. Absorption graphs were generated using UV-Vis and microparticle size was determined using DLS. The hydrocarbon structure of dielectric fluid samples has been identified using GC-MS.

7.2.1 Filtration

The total weight of contaminants removed from 3 litres of 'untreated' dielectric fluid by the filtration process was 0.57g. Therefore, filtration had a contaminant removal rate of 0.19 g L^{-1}. Contaminants of particle size 7-11µm were of greatest abundance and comprised 59.65% of the total extracted mass. The remaining contaminants were comprised of particles 12-25 µm in size, which made up 28.07% of the extracted mass, and particles of 26+ µm, which formed the remaining 12.28%. These results are summarised in *table 9*.

Table 9: Results from the filtration experiment.

<table>
<tr><th>Filter paper</th><th>Pore size (µm)</th><th colspan="2">Filter paper weight (g)</th><th colspan="2">Filter paper wet weight (g)</th><th colspan="2">Filter paper dried weight (g)</th><th>Contaminant weight (g)</th><th>Contaminant abundance (%)</th></tr>
<tr><td>Whatman grade 4</td><td>25</td><td colspan="2">0.6</td><td colspan="2">1.73</td><td colspan="2">0.67</td><td>0.07</td><td>12.28</td></tr>
<tr><td rowspan="2">Whatman grade 1</td><td rowspan="2">11</td><td>0.55</td><td rowspan="2">1.1</td><td>2.25</td><td rowspan="2">3.54</td><td>0.64</td><td rowspan="2">1.26</td><td rowspan="2">0.16</td><td rowspan="2">28.07</td></tr>
<tr><td>0.55</td><td>1.29</td><td>0.62</td></tr>
<tr><td rowspan="2">Whatman grade 3</td><td rowspan="2">6</td><td>1.14</td><td rowspan="2">2.27</td><td>2.59</td><td rowspan="2">5.49</td><td>1.25</td><td rowspan="2">2.61</td><td rowspan="2">0.34</td><td rowspan="2">59.65</td></tr>
<tr><td>1.13</td><td>2.9</td><td>1.36</td></tr>
</table>

7.2.2 Centrifugation

The total weight of contaminants extracted by centrifugation of 3x50ml 'untreated' and 'filtered' samples was 0.37g and 0.18g respectively. Therefore, for the 'untreated' sample, centrifugation had a contaminant removal rate of 2.47 g L^{-1}. A summary of the extracted contaminant weights is shown in *table 10* below.

Table 10: Weight of contaminants extracted during centrifugation experiment, from 150ml of 'untreated' and 'filtered' dielectric fluid

Sample condition	**Contaminants weight: wet (g)**	**Contaminants weight: dry (g)**	**Average dry weight (g)**
Untreated	4.32	0.37	0.37
Untreated	4.18	0.41	
Untreated	4.26	0.32	
Filtered	4.05	0.15	0.18
Filtered	4.19	0.23	
Filtered	4.02	0.17	

7.2.3 Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy

The elemental analysis of dried filter papers, used for the filtration of 'clean' and 'untreated' sample, is displayed in *figure 10* and the proportion of elemental weights extracted by filtration is summarised in *table 11*.

Table 11: Summary table of elemental weight proportions for filtration.

Element	**Elemental weight (%)**			**Overall elemental weight (%)**
	11μm filter paper	***6μm filter paper***	***25μm filter paper***	
Carbon	58.6	52.2	65.7	58.87
Oxygen	36.2	39.1	19.5	31.6
Nickel	3.3	6.0	10.0	6.43
Chromium	0.6	0.8	1.4	0.93
Cobalt	0.5	0.8	1.6	0.97
Aluminium	0.4	0.6	0.9	0.63
Silicon	0.2	0.3	0.5	0.33
Sulphur	0.2	0.2	0.4	0.27

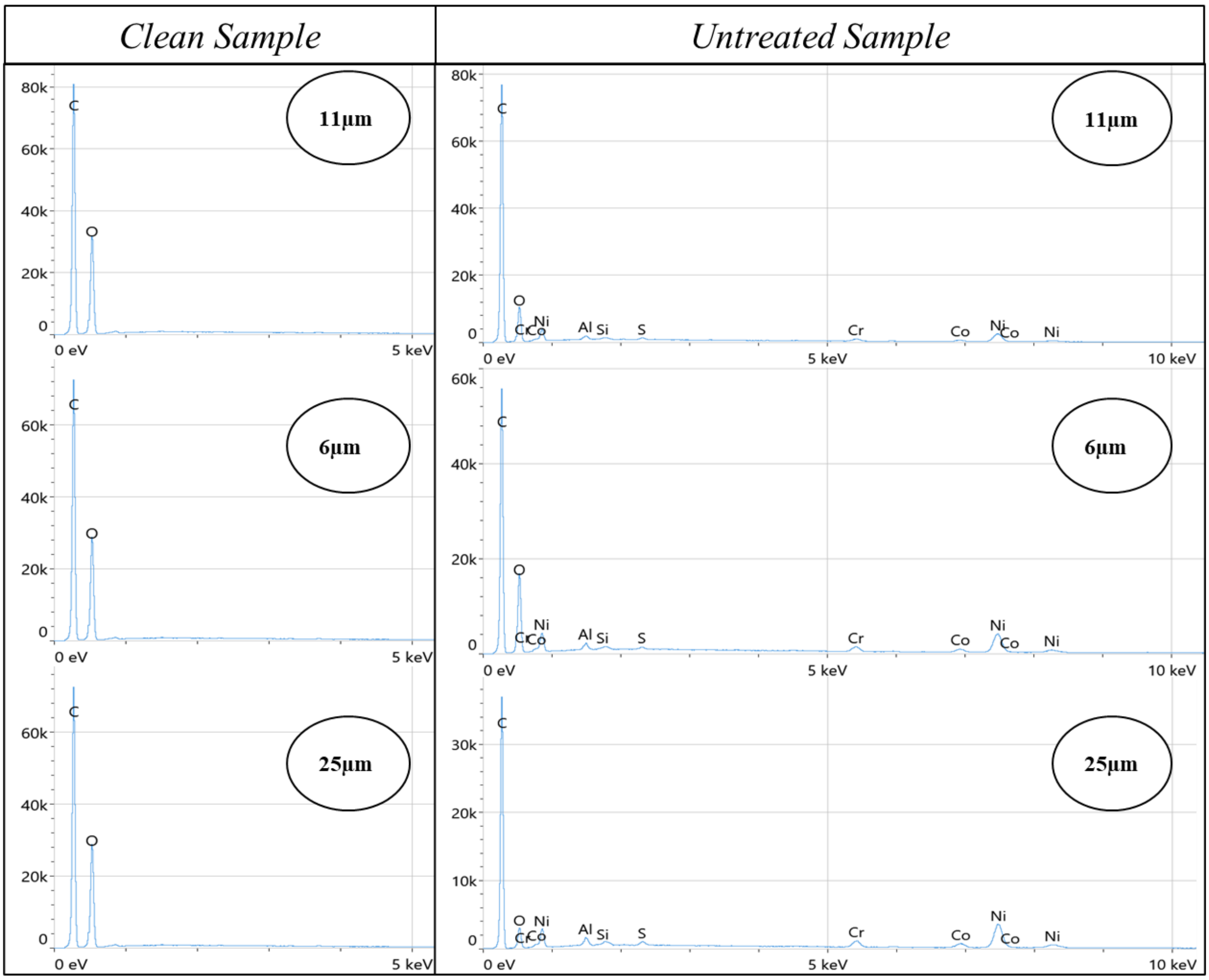

Figure 10: Side-by-side comparison of EDS results for filtration of 'clean' (left) and 'untreated' (right) sample. Results from filter papers of each pore size (11µm, 6µm, and 25µm) are shown.

Elemental analysis of the three dry samples extracted from 'untreated' dielectric fluid is summarised in *table* 12 and is displayed in figure *11*.

Table 12: Summary table of elemental weight proportions for centrifugation.

Element	Elemental weight (%)
Carbon	51.90
Nickel	20.87
Oxygen	16.27
Cobalt	3.20
Chromium	3.03
Aluminium	2.17
Boron	0.97
Silicon	0.73
Sulphur	0.67

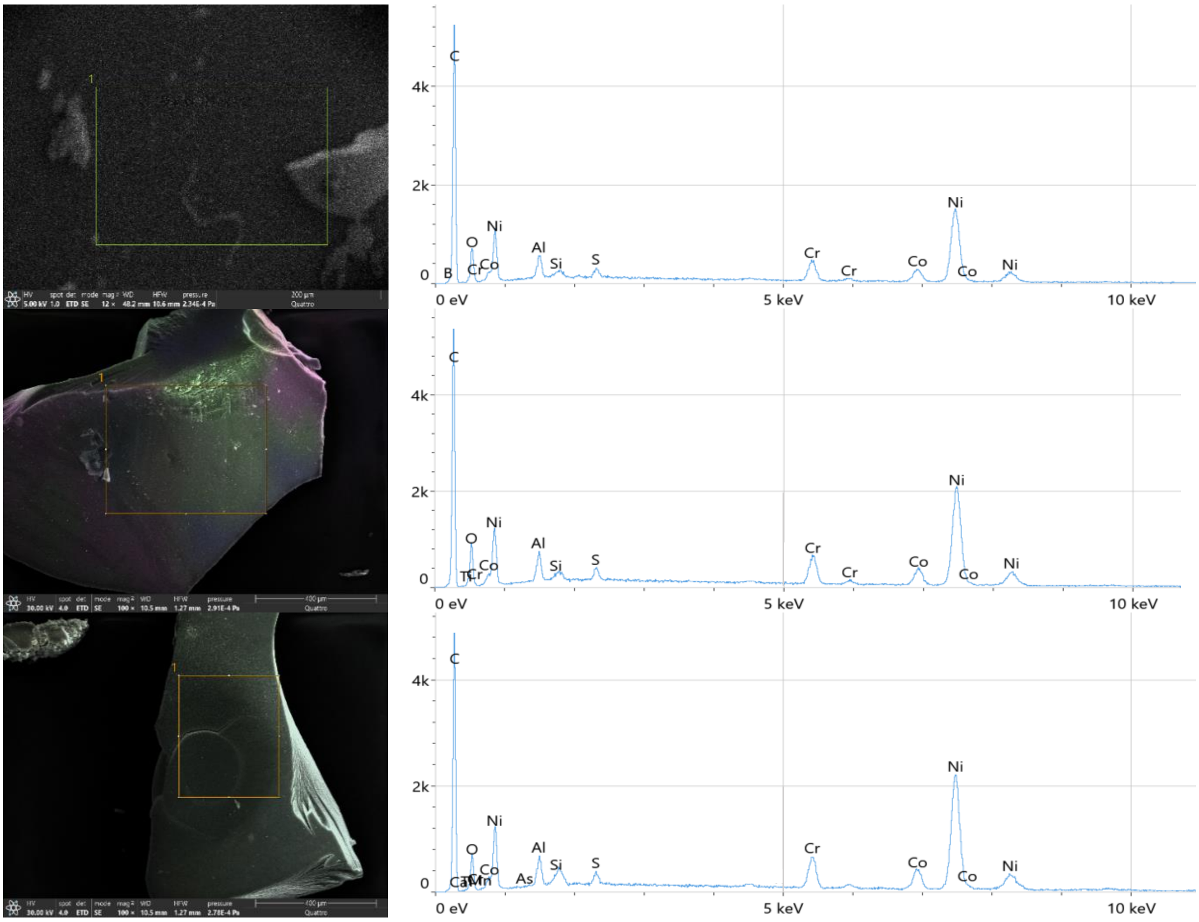

Figure 11: SEM and EDS results for dry samples extracted via centrifugation of 'untreated' sample. Three readings were taken, magnification of image ranged from 12x to 100x.

7.2.4 Ultraviolet-Visible Spectroscopy

Absorbance (*A*) values were obtained from four different dielectric fluid samples: 'Untreated (diluted)', 'filtered', 'centrifuged', and 'untreated and centrifuged'. The absorbance graphs for each sample are displayed in *figure 12* and a summary of the results are found in *table 13*. Absorbance values for the 'untreated' sample were estimated by doubling the absorbance values from the 'untreated (diluted)' sample. The wavelength maxima for each sample occurred in the range of 357nm – 363nm, indicating the likely presence of Chromium VI *(Ivanov, Figurovskaya and Shcherbakova, 2013; Sanchez-Hachair and Hofmann, 2018).*

Table 13: Summary table for peak wavelength and absorption values across a 200 - 900nm range.

Sample Condition	**Sample**	**Wavelength Maxima (nm)**	**Average Wavelength Maxima (nm)**	**Absorbance (au)**	**Average Absorbance (au)**
Untreated	1	N/A	N/A	3.352	3.327
	2	N/A		3.298	
	3	N/A		3.331	
Untreated (diluted)	1	363	359	1.657	1.662
	2	357		1.681	
	3	358		1.648	
Filtered	1	359	359.67	1.629	1.646
	2	360		1.612	
	3	360		1.697	
Centrifuged	1	357	357	0.901	0.889
	2	357		0.854	
	3	357		0.912	
Filtered and centrifuged	1	357	357	0.897	0.868
	2	357		0.841	
	3	357		0.866	
Clean	1	358	357.33	0.032	0.048
	2	357		0.059	
	3	357		0.053	

Additionally, a smaller peak occurs in the wavelength range of 480 – 482 nm (*figure 12*), with average absorbance values being the following: 'untreated' sample = 2.204 au, 'untreated (diluted)' sample = 1.102 au, 'filtered' sample = 0.861 au, 'centrifuged' sample = 0.190 au, 'filtered and centrifuged' sample = 0.138 au, and 'clean' sample = 0.005 au.

This wavelength range is consistent with the absorption wavelength of nickel II complexes (480 – 520nm) (Kumar, B. N. *et al.*, 2016). Combining this with the EDS results (*table 11* and *table 12*) suggests that nickel II is the cause of this absorption peak.

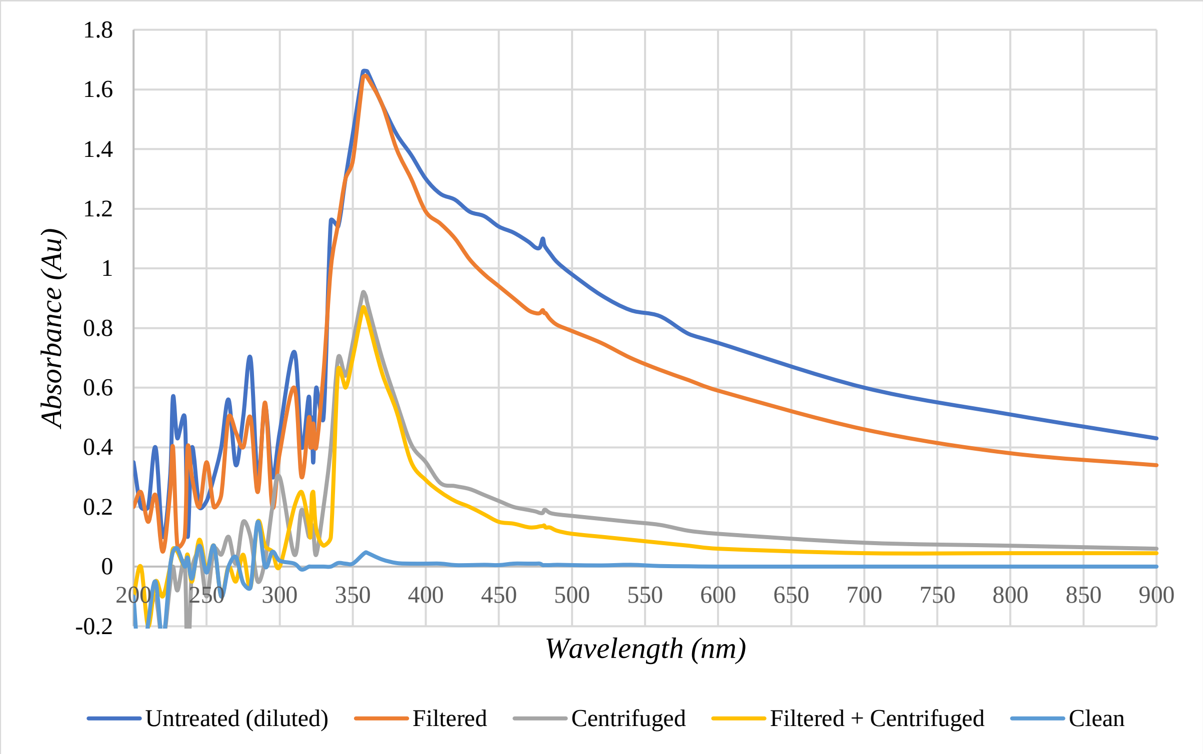

Figure 12: Absorbance graphs generated from UV-Vis analysis of five dielectric fluid samples: Untreated (diluted), filtered, centrifuged, and filtered and centrifuged, clean.

A one-way ANOVA statistical test was conducted on the absorbance values at the wavelength maxima for the dielectric fluid samples, using SPSS. The null hypothesis for this statistical test was: *The sample condition will have no impact on the mean absorbance value.* If the P value was <0.05, the null hypothesis was rejected. All sample conditions showed a significant difference in absorbance levels, with a P value <0.001, except for 'filtered' and 'untreated (diluted)' ($P = 0.981$), and 'centrifuged' and 'filtered and centrifuged' ($P = 0.941$). Therefore, dilution, filtration, and centrifugation are all shown to significantly reduce the absorbance of waste dielectric fluid. Additionally, filtering of waste dielectric fluid appears to have the same effectiveness as performing a 1:1 dilution with the clean fluid, with both reducing the absorbance of the samples by similar levels. Furthermore, centrifugation of the waste lowers the absorbance value significantly more than filtration. However, combining centrifugation with filtration to remove contaminants and lower absorbance of the sample is no more effective than centrifugation alone. The table of statistics can be found in appendices 12.4.

Chromium VI was identified as the likely contaminant within the dielectric fluid samples. Using the molar absorption coefficient of Chromium VI (2.54×10^{4} L mol^{-1} cm^{-1}) *(Saleem, 2021)*, the pathway length (1cm), the average absorbance values (*table 13*), and the Lambert-Beer law, the concentration of Chromium VI (mol L^{-1}) in each sample has been calculated. Concentration was then converted into mg L^{-1} using the atomic mass of Chromium VI (55.9961 au). Concentrations can be found in *table 14.*

Similar calculations were also performed to identify nickel II concentration in the sample. These calculations used the molar absorption coefficient of nickel II (1.40×10^{4} L mol^{-1} cm^{-1}) and the atomic mass of nickel II (59.6934 u). Concentrations can also be found in *table 14*.

Lambert-Beer Law

$$A = Kbc \rightarrow c = A/Kb$$

Concentration conversion

$$c\ (g\ L^{-1}) = c\ (mol\ L^{-1}) \times Molar\ Mass\ (au)$$

Where A = Absorbance (au), K = Molar coefficient (L mol^{-1} cm^{-1}), b = Pathway length (cm), and c = Concentration (mol L^{-1} and g L^{-1}).

Table 14: Concentration of chromium VI and nickel II in the dielectric fluid samples.

Chromium VI			
Sample Condition	**A/Kb**	**Concentration (mol L^{-1})**	**Concentration (mg L^{-1})**
Untreated	$(3.327 / (2.54x10^4x1))$	$1.31x10^{-4}$	7.33
Untreated (diluted)	$(1.662 / (2.54x10^4x1))$	$6.54x10^{-5}$	3.66
Filtered	$(1.646 / (2.54x10^4x1))$	$6.48x10^{-5}$	3.63
Centrifuged	$(0.889 / (2.54x10^4x1))$	$3.50x10^{-5}$	1.96
Filtered and centrifuged	$(0.868 / (2.54x10^4x1))$	$3.42x10^{-5}$	1.91
Clean	$(0.048 / (2.54x10^4x1))$	$1.89x10^{-6}$	0.106
Nickel II			
Sample Condition	**A/Kb**	**Concentration (mol L^{-1})**	**Concentration (mg L^{-1})**
Untreated	$(2.204/(1.4x10^4x1))$	$1.57x10^{-4}$	9.40
Untreated (diluted)	$(1.102/(1.4x10^4x1))$	$7.87x10^{-5}$	4.70
Filtered	$(0.861/(1.4x10^4x1))$	$6.15x10^{-5}$	3.67
Centrifuged	$(0.190/(1.4x10^4x1))$	$1.36x10^{-5}$	0.810
Filtered and centrifuged	$(0.138/(1.4x10^4x1))$	$9.86x10^{-6}$	0.588
Clean	$(0.005/(1.4x10^4x1))$	$3.57x10^{-7}$	0.0213

7.2.5 Dynamic Light Scattering

Size of contaminants in 'untreated' samples were too large for an accurate size distribution to be obtained via DLS, due to exceeding the 10μm limit of the Malvern Zetasizer. Results for particle size from all other samples are summarised in *table 15* below.

Table 15: Summary of contaminating microparticle diameter readings obtained through DLS.

Sample	**Modal diameter (μm)**	**Diameter range (μm)**
Untreated	>10.0	Unknown
Filtered	4.61	4.51 – 6.37
Centrifuged	2.64	2.10 – 4.80
Filtered + Centrifuged	3.73	3.54 – 4.49
Clean	1.86	1.12 – 3.15

7.2.6 Gas Chromatography Mass Spectrometry

The hydrocarbon composition and retention time for each compound remained consistent across all samples, indicating that the hydrocarbons are not broken down or altered during EDM or the contaminant separation processes. The hydrocarbon composition of all tested dielectric fluid samples can be found in appendices 12.5.

7.3 Chapter Summary

In this study chapter, microparticle contaminants within a HPM company's dielectric fluid waste have been identified and methods of cleaning this waste have been compared. Filtration and centrifugation were the methods used to separate contaminants from the waste, UV-Vis and GC-MS were performed to compare the effectiveness and viability of each technique, and SEM-EDS and DLS were used to identify and describe the contaminants.

These methods resulted in some interesting findings, for instance, the EDS analysis of removed contaminants identified the elemental composition as being carbon, nickel, cobalt, chromium, and aluminium. Following this, UV-Vis confirmed the presence of chromium VI, a harmful pollutant that poses risk to human health and the environment. Additionally, filtration removed a greater mass of contaminants from the waste than centrifugation (*0.57g vs 0.37g*) but had a lower contaminant removal rate (*0.19* gL^{-1} *vs 2.47* gL^{-1}). The modal diameter of microparticles in the 'untreated' sample exceeded the Zetasizer limit of 10μm, but this dropped to 4.61μm, 3.73μm, and 2.64μm in the 'filter', 'filtered and centrifuged', and 'centrifuged' samples respectively. However, none of these samples achieved the 1.86μm modal diameter displayed in the 'clean' sample. Both 'filtered' and 'centrifuged' samples showed a significant reduction in absorption from 'untreated' samples, but 'filtered' and 'untreated (diluted)' samples showed similar absorption levels to each other, as did 'centrifuged' and 'filtered and centrifuged'. Lastly, hydrocarbons structures and their retention times remained consistent between each sample.

The hydrocarbon structures remaining consistent between each of these samples indicates that use of the dielectric fluid throughout the EDM process does not affect its structural integrity, and neither do the contaminant removal techniques used in this study chapter. Therefore, the only factor preventing the re-use of dielectric fluid are the microparticle contaminants present in 'untreated' samples after the fluid has been used. This means there is great potential for dielectric fluid waste to be restored to its original state with the appropriate contaminant separation method. When examining the two contaminant separation methods used in this study chapter individually, they both appear to be viable methods of contaminant removal. Both significantly reduced absorbance when compared to the 'untreated' sample and both lowered the modal microparticle diameter. However, when comparing these contaminant separation methods, centrifugation appears to be the most effective. This is indicated by centrifugation having a higher contaminant removal rate than filtration and by the fact that absorption was significantly lower for 'centrifuged' samples than 'filtered' samples. Centrifugation was also more effective at removing smaller contaminants, as highlighted by the lower modal diameter of microparticles remaining in the sample. The possibility of combining both techniques was explored, but UV-Vis results showed that using filtration and centrifugation together was no more effective at lowering the absorption levels of 'untreated' sample than centrifugation alone, and the modal diameter for contaminants remaining in the 'filtered and centrifuged' sample was higher than for the 'centrifuged' sample (*3.73µm vs 2.64µm*). Therefore, centrifugation is the best contaminant separation method for HPM companies as it enables more efficient and effective contaminant removal from waste fluids. However, the practicalities of implementing a filtration system at a manufacturers site may be simpler than those of implementing centrifugation. As shown in this study chapter, filtration is able to clean a larger quantity of fluid in one go than centrifugation, which may present cost and time savings for the manufacturing company when they are attempting to clean their dielectric fluid waste. Therefore, the choice of removal technique to be implemented by the manufacturer depends on which factor they value higher; the effectiveness of contaminant removal or the speed at which large quantities of waste fluid can be cleaned.

Whether it is by filtration or centrifugation, removing contaminants from the dielectric fluid waste enables the fluid to be re-used within the EDM process. This presents massive benefits for EDM sustainability, as re-use of dielectric fluid reduces the amount of waste generated and limits hydrocarbon oil output into the environment. By doing this, the need for new material into the EDM process is reduced, enabling the manufacturing company to save money and EDM to be more financially sustainable. Additionally, as shown in study chapter one, lowering the amount of resource use and waste subsequently lowers a company's carbon footprint. Therefore, cleaning of dielectric fluid waste makes the EDM process more sustainable and contributes to Net Zero targets. Furthermore cleaning the waste in-house presents further opportunity to lower the company's carbon footprint. Due to waste treatment being an energy intensive process, the scope 3 emissions created by sending waste to these treatment plants can be significant. Conducting waste treatment in-house allows the manufacturing company to assign these energy costs to their scope 2 emissions. This presents more opportunity to lower their energy use, and subsequently their carbon footprint, as the manufacturer can control factors such as their energy supplier or on-site renewables. Therefore, this is a crucial step for a manufacturing company that is aiming to achieve Net Zero by the UK's 2050 target or earlier.

In addition to being the limiting factor for waste re-use, the microparticle contaminants also have further implications for the sustainability of the EDM process. The identified element of greatest concern was chromium VI, which is a hazardous heavy metal that poses risks for human health and is categorised as a group 1 carcinogen by the World Health Organisation (WHO). While there was a possibility that the chromium identified by EDS analysis was chromium III, which is not harmful and is an essential micronutrient (Levina and Lay, 2008), the wavelength maxima of the sample occurring in the range of 357nm – 362nm falls into the wavelength range of chromium VI, whereas the wavelength maxima for chromium III has been shown to be between 250-300nm (Ivanov, Figurovskaya and Shcherbakova, 2013; Ormaechea, Villazón and Escalera, 2017). Calculations based on UV-Vis results show that the concentration of chromium VI in 'clean' sample is 0.11 mg L^{-1}, but this significantly increases during EDM and the concentration in 'untreated' dielectric fluid waste is 7.33 mg L^{-1}. This far exceeds the 0.1 mg L^{-1} concentration that is considered safe by the US Environmental Protection Agency (EPA, 1998). According to Sun, Brocato, and Costa (2015) and the Agency for Toxic Substances and Disease Registry (ATSDR), manufacturing is a major contributor of chromium pollution, which can contaminate drinking water unless properly controlled. Additionally, chromium VI can contaminate soil, which effects plant health by impairing photosynthesis and inhibiting plant growth (Sharma *et al.*, 2022). Elevated levels of chromium VI in the soil can also present risks to humans, if this soil is used for agriculture, then chromium VI can enter the food chain and increase risk of human health conditions (Sharma *et al.*, 2022). Therefore, the effective removal of chromium VI from dielectric fluid waste is vital for both environmental and social sustainability. Another identified element within the dielectric fluid waste was nickel II. This is a priority pollutant that becomes highly toxic at elevated concentrations and, like chromium VI, can have serious ecological and human health implications (Islam, Awual and Angove, 2019). Nickel II can pollute water and soil, which can lead to its accumulation within the food chain. This is a serious risk for human health and must be avoided because ingesting high concentrations of nickel II can cause apoptosis, which could lead to cancer or neurodegenerative disease (Genchi *et al.*, 2020). As shown in the results, both filtration and centrifugation can reduce nickel II contents from dielectric fluid waste, further highlighting the importance of treating this waste fluid.

In summary, cleaning of dielectric fluid waste is a viable way to reduce the amount of waste generated from the EDM process because it can be re-used once contaminants are removed. Removing these contaminants addresses all aspects of sustainability, by having financial, social, and environmental benefits. Centrifugation is the most effective method for cleaning dielectric fluid, while filtration is also shown to have a significant impact. Performing these cleaning techniques in-house would not only reduce company expenditure on new dielectric fluid, making the EDM process more cost effective, but could also presents a chance for high precision manufacturing companies to reassign scope 3 emissions to their scope 2 emissions. Therefore, cleaning and re-using dielectric fluid waste provides opportunity for manufacturers to reach their Net Zero and sustainability targets.

7.4 Limitations

A direct comparison of elemental composition for contaminants removed by filtration against contaminants removed by centrifugation was planned, to establish if there were any differences between contaminants removed by these techniques. However, contaminants could not be isolated from the filter papers, meaning that SEM-EDS results would not have been accurate. However, the elemental composition of contaminants within dielectric fluid was still able to be determined from analysis of dried sample removed by centrifugation.

8.0 OUTCOME OF RESEARCH

Throughout this research, various ways of achieving the Net Zero and sustainability targets of a manufacturing company have been explored. The possibility of improving resource efficiency and encouraging lifecycle thinking was investigated throughout study chapter one using a behavioural study. Ways of implementing a circular economy and re-using manufacturing waste to reduce waste output were identified in study chapter two through a lab-based investigation. These study chapters answered the three research questions stated in section 4 and provide interesting insights into how a high precision manufacturing (HPM) company can reach their Net Zero and sustainability goals.

The environmental impacts of a HPM company have been established throughout this research, allowing research question one to be addressed. The material input for HPM is large, due to many resources being required for a variety of processes, such as grinding wheels and dielectric fluid. Therefore, the carbon footprint of these materials must be considered because resource use by HPM companies can substantially impact their scope 3 emissions. Not maximising the potential of resources, by discarding of viable resources or not re-using waste products where possible, causes excessive CO_{2eq} emissions from HPM companies, which makes achieving Net Zero targets more difficult. This also highlights the importance of a green supply chain. HPM companies must lower their scope 3 emissions by opting for suppliers or materials that have a lower carbon footprint. This would reduce the carbon impact of their resources which, when combined with more efficient resource use, would be a significant step towards Net Zero. However, if these issues are not addressed, HPM companies will continue to be major contributors of greenhouse gases and climate change.

While there is a big push for Net Zero, other aspects of environmental sustainability must also be considered. The subtractive manufacturing processes used by HPM companies generate waste which can be polluting. For instance, the EDM process generates chromium VI, which is a pollutant that can affect human health as well as the natural environment. Therefore, the importance of understanding elemental composition of waste material cannot be overstated. These hazardous materials could significantly impact the development of plant life, which can have serious repercussions if the pollutants contaminate agricultural land. Furthermore, while establishing the carbon footprint of grinding wheels, some unexpected environmental impacts were revealed. The global warming potential of grinding wheels was shown to be a concern, but so were aquatic and marine ecotoxicity. This is due to the manufacturing process of grinding wheels requiring a large volume of water, particularly during the mixing and moulding stages, which increases the risk of water pollution. This highlights that the manufacturing of resources used within HPM requires further research to minimise negative environmental impacts, which would assist HPM companies to become more environmentally sustainable. This research has shown that environmental impacts of HPM companies extend further than just carbon emissions. While understanding the carbon footprint of companies is important for achieving Net Zero, HPM also results in other environmental impacts that are equally concerning, such as waste materials being high in soil pollutants and the manufacturing of resources used by HPM companies producing water pollutants. Reducing these environmental impacts is vital for HPM companies to be sustainable, and their employees can have a significant role in making this happen.

Employee behaviours have a large influence on the sustainability of a manufacturing company, and ensuring employees are aware of the company's Net Zero and sustainability targets is essential for achieving these goals. This is why research question two needed to be considered. Employee understanding of these goals affects the efficiency of resource use, all resources required for HPM should be used efficiently and for their maximum lifespan to ensure the manufacturing company operate in a sustainable manner. Doing this has multiple benefits for a HPM company, such as reducing the amount of new material input required, which means less material must be bought by the company and their financial sustainability improves. Also, this limits the amount of waste generated, thus lowering the company's carbon footprint, and moving the manufacturing company closer to their Net Zero target. By taking these steps to improve resource efficiency and re-use waste, the environmental and financial sustainability of the manufacturing company can be improved. Efficient resource use also relies on appropriate provisions being made accessible to employees by the manufacturing company. This is because the Social Practice Theory of behaviour (*section 2.2*) applies to employees of a manufacturing company. This theory suggests that employees will demonstrate sustainable behaviours if they have an appropriate level of sustainability awareness, and the work environment supports them. For instance, if a re-use pile and appropriate training were provided to grinding operators then fewer resources would be wasted before they have been used for their maximum lifespan. By following ISO14001 and putting the required measures in place, HPM companies can ensure that their employees display sustainable behaviours that assist them in achieving Net Zero and sustainability targets. This research shows that sustainable employee behaviour reduces the total waste generated by HPM companies. However, some waste is unavoidable, so it is important that the environmental impact of this waste is minimised. This can be achieved by ensuring the waste contributes to a circular economy, which is addressed by research question three.

Where waste generation cannot be avoided, it is important to consider whether this can be re-used or recycled. Re-use of waste is essential for manufacturing companies to achieve sustainability targets, but this is not possible unless the contents and elemental composition of waste is completely understood. This is because waste material may contain harmful pollutants that present risks to human health and the environment, which negatively impact social and environmental sustainability. For fluid waste, these contaminants can be removed using physical separation techniques such as centrifugation and filtration. Centrifugation is the most effective of these techniques, but filtration is capable of cleaning a larger quantity of fluid at a time. Therefore, they both present viable options to manufacturing companies that wish to take more control of their waste disposal and resource use. By removing polluting material, waste fluid can then become a usable resource again, contributing to a circular economy by reducing the need for new resources to be produced. As stated earlier in this discussion, the resources used within HPM can have significant environmental impacts, therefore, limiting the requirement for new resources is a crucial step in achieving environmental sustainability and Net Zero.

To summarise, due to company culture having such an impact on employee behaviours, training should be provided to employees as this can increase their understanding of sustainability and of Net Zero. If employees have the required knowledge and awareness of the manufacturing company's targets then they are more likely to act in a way that increases financial, social, and environmental sustainability. For instance, by cleaning waste to remove pollutants and enabling waste re-use. However, employees need to have the provisions in place to act upon their increased sustainability knowledge or unnecessary waste will continue to be generated.

9.0 CONCLUSIONS AND RECOMMENDATIONS

Both study chapters have demonstrated the importance of reducing waste outputs and have shown that doing so allows the manufacturing company to use fewer new materials, lowering their costs and improving their sustainability and carbon footprint. Study chapter one demonstrated this through a behavioural study that identified how manufacturing companies can encourage their employees to behave in a more sustainable manner. For instance, adopting sustainable grinding wheel behaviours, such as using all wheels to their minimum diameter and re-using wheels across different grinding machines, was capable of saving 1.8 to 6.0 tCO_{2eq} and 310,000 to 1,030,000 litres of water annually.

Study chapter two demonstrated this through a lab-based investigation that identified polluting material within manufacturing waste and explored ways to remove this to enable safe waste re-use and disposal. For example, filtration and centrifugation reduced chromium VI concentration in waste fluid, by 3.70 mgL^{-1} and 5.37 mgL^{-1} respectively, and reduced nickel II concentration by 5.73 mgL^{-1} and 8.59 mgL^{-1} respectively.

Overall, a manufacturing company should create a carbon conscious culture for their employees through implementation of an environmental management system that follows the principles of ISO14001, meaning that company sustainability targets are communicated, employees are trained to work in a more sustainable way, and suitable provisions are put in place in order to encourage sustainable behaviours. This would allow less waste to be generated which in turn reduces the manufacturers carbon footprint. However, some waste is unavoidable, but manufacturing companies should implement cleaning systems that can remove polluting material and contaminants. By doing this, the manufacturing company can extend the usable lifespan of the waste and re-use it in their manufacturing processes. This would contribute to a circular economy, which greatly benefits the financial, social, and environmental sustainability of the manufacturer.

10.0 FURTHER RESEARCH

This research has created an estimate for the carbon equivalence of a grinding wheel. To continue this, further studies should establish carbon equivalence readings for other key materials used in different high precision manufacturing (HPM) processes. By combining these findings, a carbon baseline for all resources used in the HPM industry could be developed. Additionally, the water requirement of grinding wheel manufacturing was highlighted as an environmental concern. Further research should be conducted into the origin of water used to manufacture grinding wheels as this could have significant implications for 'freshwater aquatic' and 'marine aquatic' ecotoxicity, as well as water scarcity. Lastly, ways to improve filtration efficiency should be researched. This is because filtration is an effective method for microparticle contaminant removal, but it is less effective than centrifugation. However, by using the findings of this research there is a possibility that filtration efficiency could be improved. The metal microparticles in dielectric fluid waste have been identified, so the possibility of using magnetic filters to remove these contaminants more effectively could be explored.

11.0 REFERENCES

Abu Qudeiri, J.E., Mourad, A.I., Ziout, A., Abidi, M.H. and Elkaseer, A. (2018) 'Electric discharge machining of titanium and its alloys: review', *International journal of advanced manufacturing technology,* 96(1-4), pp. 1319-1339 Available at: 10.1007/s00170-018-1574-0.

Adejumoke, I. (2018) 'Water Pollution : Effects, Prevention, and Climatic Impact', in Glavan, M. (ed.) *Water Challenges of an Urbanizing World* IntechOpen, pp. 33-53.

Ajzen, I. (2020) 'The theory of planned behavior: Frequently asked questions', *Human behavior and emerging technologies,* 2(4), pp. 314-324 Available at: 10.1002/hbe2.195.

Ajzen, I. and Kruglanski, A.W. (2019) 'Reasoned Action in the Service of Goal Pursuit', *Psychological review,* 126(5), pp. 774-786 Available at: 10.1037/rev0000155.

Alsaifi, K., Elnahass, M., Al-Awadhi, A.M. and Salama, A. (2022) 'Carbon disclosure and firm risk: evidence from the UK corporate responses to climate change', *Eurasian business review,* 12(3), pp. 505-526 Available at: 10.1007/s40821-021-00190-0.

Altıparmak, S.C., Yardley, V.A., Shi, Z. and Lin, J. (2021) 'Challenges in additive manufacturing of high-strength aluminium alloys and current developments in hybrid additive manufacturing', *International Journal of Lightweight Materials and Manufacture,* 4(2), pp. 246-261 Available at: 10.1016/j.ijlmm.2020.12.004.

Amicarelli, V., Lagioia, G. and Bux, C. (2021) 'Global warming potential of food waste through the life cycle assessment: An analytical review', *Environmental impact assessment review,* 91, pp. 106677 Available at: 10.1016/j.eiar.2021.106677.

Andreoni, J. (1990) 'Impure Altruism and Donations to Public Goods: A Theory of Warm-Glow Giving', *The Economic journal (London),* 100(401), pp. 464-477 Available at: 10.2307/2234133.

Ascione, F., Bianco, N., Böttcher, O., Kaltenbrunner, R. and Vanoli, G.P. (2016) 'Net zero-energy buildings in Germany: Design, model calibration and lessons learned from a case-study in Berlin', *Energy and buildings,* 133, pp. 688-710 Available at: 10.1016/j.enbuild.2016.10.019.

Baliota, G.V. and Athanassiou, C.G. (2023) 'Use of paraffin oils in agriculture and beyond: back to the future', *Environmental science and pollution research international,* 30(2), pp. 2392-2405 Available at: 10.1007/s11356-022-24059-5.

Baroi, B.K., Jagadish and Patowari, P.K. (2022) 'A review on sustainability, health, and safety issues of electrical discharge machining', *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* 44(2) Available at: 10.1007/s40430-021-03351-4.

Bhatia, P., Brown, A., Cummis, C., Draucker, L., Lahd, H. and Rich, D. (2011) *Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard.*

Bhattacharyya, B. and Doloi, B. (2020) *Modern machining technology : advanced, hybrid, micro machining and super finishing technology.* San Diego, CA, United States: Academic Press, an imprint of Elsevier.

Birdwell, J.E. and Engel, A.S. (2010) 'Characterization of dissolved organic matter in cave and spring waters using UV–Vis absorbance and fluorescence spectroscopy', *Organic geochemistry,* 41(3), pp. 270-280 Available at: 10.1016/j.orggeochem.2009.11.002.

Birou, L.M., Green, K.W. and Inman, R.A. (2019) 'Sustainability knowledge and training: outcomes and firm performance', *Journal of manufacturing technology management,* 30(2), pp. 294-311 Available at: 10.1108/JMTM-05-2018-0148.

Bisinella, V., Götze, R., Conradsen, K., Damgaard, A., Christensen, T.H. and Astrup, T.F. (2017) 'Importance of waste composition for Life Cycle Assessment of waste management solutions', *Journal of cleaner production,* 164, pp. 1180-1191 Available at: 10.1016/j.jclepro.2017.07.013.

Boulay, A., Verones, F. and Vázquez-Rowe, I. (2021) 'Marine plastics in LCA: current status and MarILCA's contributions', *The international journal of life cycle assessment,* 26(11), pp. 2105-2108 Available at: 10.1007/s11367-021-01975-1.

Buaisha, M., Balku, S. and Yaman, ŞÖ (2020) 'Heavy Metal Removal Investigation in Conventional Activated Sludge Systems', *Civil Engineering Journal,* 6(3), pp. 470-477 Available at: 10.28991/cej-2020-03091484.

Byrne, G. (2007) 'A Statistical Primer: Understanding Descriptive and Inferential Statistics', *Evidence Based Library and Information Practice,* 2(1), pp. 32-47 Available at: 10.18438/B8FW2H.

Catalano, A.R., Debernardi, L., Balaso, R., Rubbiani, F., Priarone, P.C. and Settineri, L. (2022) 'An appraisal of the cradle-to-gate energy demand and carbon footprint of high-speed steel cutting tools', *Procedia CIRP,* 105, pp. 745-750 Available at: 10.1016/j.procir.2022.02.124.

Cerdà, V., Phansi, P. and Ferreira, S. (2022) 'From mono- to multicomponent methods in UV-VIS spectrophotometric and fluorimetric quantitative analysis – A review', *TrAC, Trends in analytical chemistry (Regular ed.),* 157, pp. 116772 Available at: 10.1016/j.trac.2022.116772.

Chao, Y. (2012) 'Predicting people's environmental behaviour: theory of planned behaviour and model of responsible environmental behaviour', *Environmental education research,* 18(4), pp. 437-461 Available at: 10.1080/13504622.2011.634970.

Climate Change Committee, (2021). *Independent Assessment of UK Climate Risk.* Available at: https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/ (Accessed: July 2022).

Conkle, J.L., Báez Del Valle, C.D. and Turner, J.W. (2018) 'Are We Underestimating Microplastic Contamination in Aquatic Environments?', *Environmental management (New York),* 61(1), pp. 1-8 Available at: 10.1007/s00267-017-0947-8.

Department for Business, Energy, and Industrial Stratergy (2022) *2020 UK Greenhouse Gas Emissions, Final Figures.* London: HM Government. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf (Accessed: 27 June 2023).

Department for Energy Security and Net Zero (2021) *Net Zero Strategy: Build Back Greener.* London: HM Government. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf (Accessed: 27 June 2023).

Department for Energy Security and Net Zero (2023) *Powering Up Britain: The Net Zero Growth Plan.* London: HH Global. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147457/powering-up-britain-net-zero-growth-plan.pdf (Accessed: 27 June 2023).

Department of Energy and Climate Change (2011) *The Carbon Plan: Delivering our low carbon future.* London: HM Government. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf (Accessed: 27 June 2023).

Devi, K.G., Ravindran, M. and Kumar, S.S. (2016) 'Analysis of critical parameters of vegetable oil as an alternate dielectric fluid to mineral oil', *2016 10th International Conference on Intelligent Systems and Control (ISCO), ,* pp. 1-5 Available at: 10.1109/ISCO.2016.7726885.

Dhakar, K., Kumar, R., Katheria, A., Nagdeve, L. and Kumar, H. (2022) 'Effect of various dielectric fluids on electric discharge machining (EDM): a review', *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* 44(10) Available at: 10.1007/s40430-022-03778-3.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N. and Tassin, B. (2015) 'Microplastic contamination in an urban area: a case study in Greater Paris', *Environmental chemistry,* 12(5), pp. 592-599 Available at: 10.1071/EN14167.

Dwivedi, A.P. and Choudhury, S.K. (2018) 'A Preliminary Study of the Air Pollutants Discharge During the Electric Discharge Machining Process'*Green Buildings and Sustainable Engineering* Singapore: Springer Singapore, pp. 467-475.

Elmaraghy, W.H., Nada, O.A. and Elmaraghy, H.A. (2008) 'Quality prediction for reconfigurable manufacturing systems via human error modelling', *International journal of computer integrated manufacturing,* 21(5), pp. 584-598 Available at: 10.1080/09511920701233464.

EPA (1998) *Environmental Protection Agency: National Primary Drinking Water Regulations--Interim Enhanced Surface Water Treatment. Congressional Publications*.

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H. and Amato, S. (2013) 'Microplastic pollution in the surface waters of the Laurentian Great Lakes', *Marine pollution bulletin,* 77(1-2), pp. 177-182 Available at: 10.1016/j.marpolbul.2013.10.007.

Feigin, S., Owens, G. and Goodyear-Smith, F. (2014) 'Theories of human altruism: a systematic review', *Journal of Psychiatry and Brain Functions,* 1(1), pp. 5 Available at: 10.7243/2055-3447-1-5.

Finkbeiner, M. (2014) 'The International Standards as the Constitution of Life Cycle Assessment: The ISO 14040 Series and its Offspring'*Background and Future Prospects in Life Cycle Assessment* Dordrecht: Springer Netherlands, pp. 85-106.

Fujiki, M., Ni, J. and Shih, A.J. (2009) 'Investigation of the effects of electrode orientation and fluid flow rate in near-dry EDM milling', *International journal of machine tools & manufacture,* 49(10), pp. 749-758 Available at: 10.1016/j.ijmachtools.2009.05.003.

Gaim, M., Clegg, S. and Cunha, M.P.e. (2021) 'Managing Impressions Rather Than Emissions: Volkswagen and the false mastery of paradox', *Organization studies,* 42(6), pp. 949-970 Available at: 10.1177/0170840619891199.

Gärling, T., Fujii, S., Gärling, A. and Jakobsson, C. (2003) 'Moderating effects of social value orientation on determinants of proenvironmental behavior intention', *Journal of environmental psychology,* 23(1), pp. 1-9 Available at: 10.1016/S0272-4944(02)00081-6.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M.S. and Catalano, A. (2020) 'Nickel: Human Health and Environmental Toxicology', *International Journal of Environmental Research and Public Health,* 17(3), pp. 679 Available at: 10.3390/ijerph17030679.

Ghamkhar, R., Boxman, S.E., Main, K.L., Zhang, Q., Trotz, M.A. and Hicks, A. (2021) 'Life cycle assessment of aquaculture systems: Does burden shifting occur with an increase in production intensity?', *Aquacultural engineering,* 92, pp. 102130 Available at: 10.1016/j.aquaeng.2020.102130.

Gholipoor, A., Baseri, H. and Shabgard, M.R. (2015) 'Investigation of near dry EDM compared with wet and dry EDM processes', *Journal of mechanical science and technology,* 29(5), pp. 2213-2218 Available at: 10.1007/s12206-015-0441-2.

Giménez-Campillo, C., Pastor-Belda, M., Campillo, N., Hernández-Córdoba, M. and Viñas, P. (2021) 'Development of a new methodology for the determination of N-nitrosamines impurities in ranitidine pharmaceuticals using microextraction and gas chromatography-mass spectrometry', *Talanta (Oxford),* 223(Pt 2), pp. 121659 Available at: 10.1016/j.talanta.2020.121659.

Gniadek, M. and Dąbrowska, A. (2019) 'The marine nano- and microplastics characterisation by SEM-EDX: The potential of the method in comparison with various physical and chemical approaches', *Marine pollution bulletin,* 148, pp. 210-216 Available at: 10.1016/j.marpolbul.2019.07.067.

Grimmer, M. and Miles, M.P. (2017) 'With the best of intentions: a large sample test of the intention-behaviour gap in pro-environmental consumer behaviour', *International journal of consumer studies,* 41(1), pp. 2-10 Available at: 10.1111/ijcs.12290.

Gudde, P., Oakes, J., Cochrane, P., Caldwell, N. and Bury, N. (2021) 'The role of UK local government in delivering on net zero carbon commitments: You've declared a Climate Emergency, so what's the plan?', *Energy policy,* 154, pp. 112245 Available at: 10.1016/j.enpol.2021.112245.

Gunatilake, S.K. (2015) 'Methods of Removing Heavy Metals from Industrial Wastewater', Available at: 10.13140/Rhttps://www.researchgate.net/publication/287818349_Methods_of_Removing_Heavy_Metals_from_Industrial_WastewaterG.2.1.3751.1848.

Guo, Liu, C., Ye, R. and Duan, Q. (2020) 'Advances on Water Quality Detection by UV-Vis Spectroscopy', *Applied sciences,* 10(19), pp. 6874 Available at: 10.3390/app10196874.

Guspita, D. and Ulianas, A. (2020) 'Optimization of complex NH3 with Cu2+ ions to determine levels of ammonia by UV-Vis spectrophotometer', *Journal of physics. Conference series,* 1481(1) Available at: 10.1088/1742-6596/1481/1/012040.

Hargreaves, T. (2011) 'Practice-ing behaviour change: Applying social practice theory to pro-environmental behaviour change', *Journal of consumer culture,* 11(1), pp. 79-99 Available at: 10.1177/1469540510390500.

Harland, P., Staats, H. and Wilke, H.A.M. (2007) 'Situational and Personality Factors as Direct or Personal Norm Mediated Predictors of Pro-environmental Behavior: Questions Derived From Norm-activation Theory', *Basic and applied social psychology,* 29(4), pp. 323-334 Available at: 10.1080/01973530701665058.

Hembach, N., Alexander, J., Hiller, C., Wieland, A. and Schwartz, T. (2019) 'Dissemination prevention of antibiotic resistant and facultative pathogenic bacteria by ultrafiltration and ozone treatment at an urban wastewater treatment plant', *Scientific reports,* 9(1), pp. 12843-12 Available at: 10.1038/s41598-019-49263-1.

Herfeld, C. (2020) 'The Diversity of Rational Choice Theory: A Review Note', *Topoi,* 39(2), pp. 329-347 Available at: 10.1007/s11245-018-9588-7.

Hertwich, E.G. and Wood, R. (2018) 'The growing importance of scope 3 greenhouse gas emissions from industry', *Environmental research letters,* 13(10), pp. 104013 Available at: 10.1088/1748-9326/aae19a.

Hildebrandt, L., Voigt, N., Zimmermann, T., Reese, A. and Proefrock, D. (2019) 'Evaluation of continuous flow centrifugation as an alternative technique to sample microplastic from water bodies', *Marine environmental research,* 151, pp. 104768 Available at: 10.1016/j.marenvres.2019.104768.

Hoehl, S., Keupp, S., Schleihauf, H., McGuigan, N., Buttelmann, D. and Whiten, A. (2019) '‘Over-imitation’: A review and appraisal of a decade of research', *Developmental review,* 51, pp. 90-108 Available at: 10.1016/j.dr.2018.12.002.

Hsieh, M., Tung, C., Yao, W., Wu, M. and Liao, Y. (2007) 'Servo design of a vertical axis drive using dual linear motors for high speed electric discharge machining', *International journal of machine tools & manufacture,* 47(3), pp. 546-554 Available at: 10.1016/j.ijmachtools.2006.05.011.

Huang, G., He, J., Zhang, X., Feng, M., Tan, Y., Lv, C., Huang, H. and Jin, Z. (2021) 'Applications of Lambert-Beer law in the preparation and performance evaluation of graphene modified asphalt', *Construction & building materials,* 273, pp. 121582 Available at: 10.1016/j.conbuildmat.2020.121582.

Huijbregts, M.A.J., Breedveld, L., Huppes, G., de Koning, A., van Oers, L. and Suh, S. (2003) 'Normalisation figures for environmental life-cycle assessment: The Netherlands (1997/1998), Western Europe (1995) and the world (1990 and 1995)', *Journal of cleaner production,* 11(7), pp. 737-748 Available at: 10.1016/S0959-6526(02)00132-4.

Islam, M.A., Awual, M.R. and Angove, M.J. (2019) 'A review on nickel(II) adsorption in single and binary component systems and future path', *Journal of environmental chemical engineering,* 7(5), pp. 103305 Available at: 10.1016/j.jece.2019.103305.

Ivanov, V.M., Figurovskaya, V.N. and Shcherbakova, Y.I. (2013) 'Chromaticity characteristics of chromium(VI) solutions', *Moscow University chemistry bulletin,* 68(4), pp. 191-195 Available at: 10.3103/S0027131413040056.

Jackson, T. (2005) *Motivating Sustainable Consumption a review of evidence on consumer behaviour and behavioural change.* Centre for Environmental Strategy: Available at:(Accessed: .

Jianbao, F., Shunqun, L. and Lihang, C. (2021) *Centrifugation method for reducing heavy metal content in sediment.* Piscataway: IEEE, pp. 291.

Johnstone, L. and Hallberg, P. (2020) 'ISO 14001 adoption and environmental performance in small to medium sized enterprises', *Journal of environmental management,* 266, pp. 110592 Available at: 10.1016/j.jenvman.2020.110592.

Kansal, H.K., Singh, S. and Kumar, P. (2007) 'Technology and research developments in powder mixed electric discharge machining (PMEDM)', *Journal of materials processing technology,* 184(1), pp. 32-41 Available at: 10.1016/j.jmatprotec.2006.10.046.

Kapil, S., Legesse, F., Kumar, R. and Karunakaran, K.P. (2017) 'Hybrid Layered Manufacturing of Turbine Blades', *Materials Today: Proceedings,* 4(8), pp. 8837-8847 Available at: 10.1016/j.matpr.2017.07.234.

Käppler, A., Fischer, D., Oberbeckmann, S., Schernewski, G., Labrenz, M., Eichhorn, K. and Voit, B. (2016) 'Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both?', *Analytical and bioanalytical chemistry,* 408(29), pp. 8377-8391 Available at: 10.1007/s00216-016-9956-3.

Kaur, G., Singh, H. and Singh, J. (2020) 'UV-vis spectrophotometry for environmental and industrial analysis'*Green Sustainable Process for Chemical and Environmental Engineering and Science* United States: Elsevier.

Kendall, A. (2012) 'Time-adjusted global warming potentials for LCA and carbon footprints', *The international journal of life cycle assessment,* 17(8), pp. 1042-1049 Available at: 10.1007/s11367-012-0436-5.

Kirchherr, J., Reike, D. and Hekkert, M. (2017) 'Conceptualizing the circular economy: An analysis of 114 definitions', *Resources, conservation and recycling,* 127, pp. 221-232 Available at: 10.1016/j.resconrec.2017.09.005.

Kliuev, M., Boccadoro, M., Perez, R., Dal Bó, W., Stirnimann, J., Kuster, F. and Wegener, K. (2016) 'EDM Drilling and Shaping of Cooling Holes in Inconel 718 Turbine Blades', *Procedia CIRP,* 42, pp. 322-327 Available at: 10.1016/j.procir.2016.02.293.

Konan, F.K., Betié, A., Nkuissi, H.J.T., Dakshi, K., Aka, B. and Hartiti, B. (2017) 'SEM/EDX, UV-Vis-NIR spectroscopy and refractive index studies of zinc oxide thin films', *Journal of Ceramic Processing Research, 18(12),* , pp. 882-886.

Krahnstöver, T., Hochstrat, R. and Wintgens, T. (2019) 'Comparison of methods to assess the integrity and separation efficiency of ultrafiltration membranes in wastewater reclamation processes', *Journal of Water Process Engineering,* 30, pp. 100646 Available at: 10.1016/j.jwpe.2018.06.008.

Kroneberg, C. and Kalter, F. (2012) 'Rational Choice Theory and Empirical Research: Methodological and Theoretical Contributions in Europe', *Annual review of sociology,* 38(1), pp. 73-92 Available at: 10.1146/annurev-soc-071811-145441.

Kuhar, N., Sil, S., Verma, T. and Umapathy, S. (2018) 'Challenges in application of Raman spectroscopy to biology and materials', *RSC advances,* 8(46), pp. 25888-2598 Available at: 10.1039/c8ra04491k.

Kumar, B.N., Kanchi, S., Sabela, M.I., Bisetty, K. and Jyothi, N.V.V. (2016) 'Spectrophotometric determination of nickel (II) in waters and soils: Novel chelating agents and their biological applications supported by DFT method', *Karbala International Journal of Modern Science,* 2(4), pp. 239-250 Available at: 10.1016/j.kijoms.2016.08.003.

Kumar, R., Sarkar, B., Bhatt, B.P., Mali, S.S., Mondal, S., Mishra, J.S., Jat, R.K., Meena, R.S., Anurag, A.P. and Raman, R.K. (2021) 'Comparative assessment of energy flow, carbon auditing and ecoefficiency of diverse tillage systems for cleaner and sustainable crop production in eastern India', *Journal of cleaner production,* 293, pp. 126162 Available at: 10.1016/j.jclepro.2021.126162.

Kumar, S., Singh, R., Singh, T.P. and Sethi, B.L. (2009) 'Surface modification by electrical discharge machining: A review', *Journal of materials processing technology,* 209(8), pp. 3675-3687 Available at: 10.1016/j.jmatprotec.2008.09.032.

Kumar and Dhanabalan, S. (2019) 'Influence on machinability and form tolerance of Inconel 718 in Edm using different diameter multi hole Cu electrodes', *SN Applied Sciences,* 1(5) Available at: 10.1007/s42452-019-0403-x.

Kuramochi, T., Roelfsema, M., Hsu, A., Lui, S., Weinfurter, A., Chan, S., Hale, T., Clapper, A., Chang, A. and Höhne, N. (2020) 'Beyond national climate action: the impact of region, city, and business commitments on global greenhouse gas emissions', *Climate policy,* 20(3), pp. 275-291 Available at: 10.1080/14693062.2020.1740150.

La Fata, C.M., Adelfio, L., Micale, R. and La Scalia, G. (2023) 'Human error contribution to accidents in the manufacturing sector: A structured approach to evaluate the interdependence among performance shaping factors', *Safety science,* 161, pp. 106067 Available at: 10.1016/j.ssci.2023.106067.

Laveglia, A., Ukrainczyk, N., De Belie, N. and Koenders, E. (2023) 'Decarbonizing the lime-based construction materials industry: A practical guide for cradle-to-gate life-cycle inventory', Sustainable production and consumption, 40, pp. 194-209 Available at: 10.1016/j.spc.2023.06.021.

Lavrik, N.L. and Mulloev, N.U. (2017) 'Estimation of the molar absorption coefficient of copper salicylate within the spectral range 300–350 nm', *Spectrochimica acta. Part A, Molecular and biomolecular spectroscopy,* 187, pp. 36-38 Available at: 10.1016/j.saa.2017.06.012.

Law, Y., Ye, L., Pan, Y. and Yuan, Z. (2012) 'Nitrous oxide emissions from wastewater treatment processes', *Philosophical Transactions of the Royal Society B: Biological Sciences,* 367(1593), pp. 1265-1277 Available at: 10.1098/rstb.2011.0317.

Leal Filho, W., Eustachio, J.H.P.P., Caldana, A.C.F., Will, M., Lange Salvia, A., Rampasso, I.S., Anholon, R., Platje, J. and Kovaleva, M. (2020) 'Sustainability Leadership in Higher Education Institutions: An Overview of Challenges', *Sustainability,* 12(9), pp. 3761 Available at: 10.3390/su12093761.

Leão, F.N. and Pashby, I.R. (2004) 'A review on the use of environmentally-friendly dielectric fluids in electrical discharge machining', *Journal of materials processing technology,* 149(1), pp. 341-346 Available at: 10.1016/j.jmatprotec.2003.10.043.

Lee, S., Kurade, M.B., Jeon, B., Kim, J., Zheng, Y. and Salama, E. (2021) 'Water condition in biotrickling filtration for the efficient removal of gaseous contaminants', *Critical reviews in biotechnology,* 41(8), pp. 1279-1296 Available at: 10.1080/07388551.2021.1917506.

Leppert, T. (2018) 'A review on ecological and health impacts of electro discharge machining (EDM)', *AIP Conference Proceedings,* 2017(1) Available at: 10.1063/1.5056277.

Levina, A. and Lay, P.A. (2008) 'Chemical Properties and Toxicity of Chromium(III) Nutritional Supplements', *Chemical research in toxicology,* 21(3), pp. 563-571 Available at: 10.1021/tx700385t.

Li, C.J., Li, Y., Tong, H., Zhao, L., Kong, Q.C. and Wang, Z.Q. (2016) 'An EDM pulse power generator and its feasible experiments for drilling film cooling holes', *International journal of advanced manufacturing technology,* 87(5-8), pp. 1813-1821 Available at: 10.1007/s00170-016-8598-0.

Li, L., Xu, G., Yu, H. and Xing, J. (2018) 'Dynamic membrane for micro-particle removal in wastewater treatment: Performance and influencing factors', *The Science of the total environment,* 627, pp. 332-340 Available at: 10.1016/j.scitotenv.2018.01.239.

Li, Wiedmann, T. and Hadjikakou, M. (2020) 'Enabling Full Supply Chain Corporate Responsibility: Scope 3 Emissions Targets for Ambitious Climate Change Mitigation', *Environmental science & technology,* 54(1), pp. 400-411 Available at: 10.1021/acs.est.9b05245.

Liu, Y., Wang, P., Luo, X., Zhang, M., Zhao, T., Yang, Y., Sun, Y., Liu, X. and Liu, J. (2022) 'Analysis of Flexible Energy Use Behavior of Rural Residents Based on Two-stage Questionnaire: A Case Study in Xi'an, China', *Energy and buildings,* 269, pp. 112246 Available at: 10.1016/j.enbuild.2022.112246.

Longoria-Rodríguez, F.E., González, L.T., Mancilla, Y., Acuña-Askar, K., Arizpe-Zapata, J.A., González, J., Kharissova, O.V. and Mendoza, A. (2021) 'Sequential SEM-EDS, PLM, and MRS Microanalysis of Individual Atmospheric Particles: A Useful Tool for Assigning Emission Sources', *Toxics (Basel),* 9(2), pp. 37 Available at: 10.3390/toxics9020037.

Machnik-Słomka, J. and Kłosok-Bazan, I. (2017) 'The problem of environmental awareness in terms of the eco-innovation implementation in enterprises', *Economic and Environmental Studies (E&ES),* 17(2), pp. 221-234.

Majchrzak, T., Wojnowski, W., Lubinska-Szczygeł, M., Różańska, A., Namieśnik, J. and Dymerski, T. (2018) 'PTR-MS and GC-MS as complementary techniques for analysis of volatiles: A tutorial review', *Analytica chimica acta,* 1035, pp. 1-13 Available at: 10.1016/j.aca.2018.06.056.

Marisamynathan and Perumal, V. (2014) 'Study on pedestrian crossing behavior at signalized intersections', *Journal of Traffic and Transactions Engineering （English Edition）,* 1(2), pp. 103-110 Available at: 10.1016/S2095-7564(15)30094-5.

Marteau, T.M., Chater, N. and Garnett, E.E. (2021) 'Changing behaviour for net zero 2050', *British Medical Journal,* 375(8309), pp. 67.

McGuirk, P.M. and O'Neill, P. (2010) 'Using questionnaires in qualitative human geography' Oxford University Press.

McKeown, P.A. (1987) 'The Role of Precision Engineering in Manufacturing of the Future', *CIRP annals,* 36(2), pp. 495-501 Available at: 10.1016/S0007-8506(07)60751-3.

Mekhamer, W. and Al-Tamimi, S. (2019) 'Removal of ciprofloxacin from simulated wastewater by pomegranate peels', *Environmental science and pollution research international,* 26(3), pp. 2297-2304 Available at: 10.1007/s11356-018-3639-x.

MET Office (2022) *UK Climate Projections: Headline Findings. Available at: (Accessed: August 2022).* . Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_headline_findings_v4_aug22.pdf (Accessed: November 2022).

Mikac, L., Kovačević, E., Ukić, Š, Raić, M., Jurkin, T., Marić, I., Gotić, M. and Ivanda, M. (2021) 'Detection of multi-class pesticide residues with surface-enhanced Raman spectroscopy', *Spectrochimica acta. Part A, Molecular and biomolecular spectroscopy,* 252, pp. 119478 Available at: 10.1016/j.saa.2021.119478.

Mikac, L., Marić, I., Štefanić, G., Jurkin, T., Ivanda, M. and Gotić, M. (2019) 'Radiolytic synthesis of manganese oxides and their ability to decolorize methylene blue in aqueous solutions', *Applied surface science,* 476, pp. 1086-1095 Available at: 10.1016/j.apsusc.2019.01.212.

Mishra, B.P. and Routara, B.C. (2020) 'Evaluation of technical feasibility and environmental impact of Calophyllum Inophyllum (Polanga) oil based bio-dielectric fluid for green EDM', *Measurement : journal of the International Measurement Confederation,* 159, pp. 107744 Available at: 10.1016/j.measurement.2020.107744.

Mohd Abbas, N., Solomon, D.G. and Fuad Bahari, M. (2007) 'A review on current research trends in electrical discharge machining (EDM)', *International journal of machine tools & manufacture,* 47(7), pp. 1214-1228 Available at: 10.1016/j.ijmachtools.2006.08.026.

Mullally, G., Revez, A., Harris, C., Dunphy, N., Rogan, F., Byrne, E.P., McGookin, C., Ó Gallachóir, B.P., Bolger, P., O'Dwyer, B., Flood, S., Boyle, E., Glynn, J., Barry, J. and Ellis, G. (2022) *A roadmap for local deliberative engagements on transitions to net zero carbon and climate resilience.* Environmental Protection Agency. Available at: http://hdl.handle.net/10468/13447 (Accessed: .

Nair, S., Dutta, A., R, N. and Giridharan, A. (2019) 'Investigation on EDM machining of Ti6Al4V with negative polarity brass electrode', *Materials and manufacturing processes,* 34(16), pp. 1824-1831 Available at: 10.1080/10426914.2019.1675891.

Ness, D.A. and Xing, K. (2017) 'Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model', *Journal of industrial ecology,* 21(3), pp. 572-592 Available at: 10.1111/jiec.12586.

Nguyen, M.D., Rahman, M. and Wong, Y.S. (2012) 'An experimental study on micro-EDM in low-resistivity deionized water using short voltage pulses', *International journal of advanced manufacturing technology,* 58(5-8), pp. 533-544 Available at: 10.1007/s00170-011-3397-0.

Nguyen, P.H., Banh, T.L., Mashood, K.A., Tran, D.Q., Dong Pham, V., Muthuramalingam, T., Duc Nguyen, V. and Nguyen, D.T. (2020) 'Application of TGRA-Based Optimisation for Machinability of High-Chromium Tool Steel in the EDM Process', *Arabian journal for science and engineering (2011),* 45(7), pp. 5555-5562 Available at: 10.1007/s13369-020-04456-z.

Ogu, M.I. (2013) 'Rational Choice Theory: Assumptions , Strengths , and Greatest Weaknesses in Application Outside the Western Milieu Context', *Nigerian Chapter of Arabian Journal of Business and Management Review,* 1(3), pp. 90-99 Available at: 10.12816/0003628.

Onchoke, K.K. and Sasu, S.A. (2016) 'Determination of Hexavalent Chromium (Cr(VI)) Concentrations via Ion Chromatography and UV-Vis Spectrophotometry in Samples Collected from Nacogdoches Wastewater Treatment Plant, East Texas (USA)', *Advances in Environmental Chemistry,* 2016, pp. 1-10 Available at: 10.1155/2016/3468635.

Ormaechea, O., Villazón, A. and Escalera, R. (2017) 'A spectrometer based on smartphones and a low-cost kit for transmittance and absorbance measurements in real-time', *Optica Pura y Aplicada,* 50(3), pp. 239-249 Available at: 10.7149/OPA.50.3.49053.

Panepinto, D., Fiore, S., Zappone, M., Genon, G. and Meucci, L. (2016) 'Evaluation of the energy efficiency of a large wastewater treatment plant in Italy', *Applied energy,* 161, pp. 404-411 Available at: 10.1016/j.apenergy.2015.10.027.

Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M. and Ituarte, I.F. (2016) 'Comparative environmental impacts of additive and subtractive manufacturing technologies', *CIRP annals,* 65(1), pp. 29-32 Available at: 10.1016/j.cirp.2016.04.036.

Pellegrini, G. and Ravasio, C. (2020) 'A sustainability index for the micro-EDM drilling process', *Journal of cleaner production,* 247, pp. 119136 Available at: 10.1016/j.jclepro.2019.119136.

Penuel, W.R., Van Horne, K., DiGiacomo, D. and Kirshner, B. (2017) 'A Social Practice Theory of Learning and Becoming Across Contexts and Time', *Front Learning Research,* 4(4), pp. 30-38 Available at: 10.14786/flr.v4i4.205.

Peters, C.N. and Evans, I.E.J. (2016) 'Automated Processing of Plasma Samples for Lipoprotein Separation by Rate-Zonal Ultracentrifugation', *Journal of Laboratory Automation,* 21(6), pp. 756-764 Available at: 10.1177/2211068215623210.

Petry, T., Bury, D., Fautz, R., Hauser, M., Huber, B., Markowetz, A., Mishra, S., Rettinger, K., Schuh, W. and Teichert, T. (2017) 'Review of data on the dermal penetration of mineral oils and waxes used in cosmetic applications', *Toxicology letters,* 280, pp. 70-78 Available at: 10.1016/j.toxlet.2017.07.899.

Pfister, S., Vionnet, S., Levova, T. and Humbert, S. (2016) 'Ecoinvent 3: assessing water use in LCA and facilitating water footprinting', *The international journal of life cycle assessment,* 21(9), pp. 1349-1360 Available at: 10.1007/s11367-015-0937-0.

Pires, A. and Martinho, G. (2019) 'Waste hierarchy index for circular economy in waste management', *Waste management (Elmsford),* 95, pp. 298-305 Available at: 10.1016/j.wasman.2019.06.014.

Pivnenko, K. and Astrup, T.F. (2016) 'The challenge of chemicals in material lifecycles', *Waste management (Elmsford),* 56, pp. 1-2 Available at: 10.1016/j.wasman.2016.08.016.

Priya, A.K., Gnanasekaran, L., Dutta, K., Rajendran, S., Balakrishnan, D. and Soto-Moscoso, M. (2022) 'Biosorption of heavy metals by microorganisms: Evaluation of different underlying mechanisms', *Chemosphere (Oxford),* 307, pp. 135957 Available at: 10.1016/j.chemosphere.2022.135957.

Qian, W., Hörisch, J. and Schaltegger, S. (2018) 'Environmental management accounting and its effects on carbon management and disclosure quality', *Journal of cleaner production,* 174, pp. 1608-1619 Available at: 10.1016/j.jclepro.2017.11.092.

Qiu, Y., Lee, B.E., Ruecker, N.J., Neumann, N., Ashbolt, N. and Pang, X. (2016) 'A one-step centrifugal ultrafiltration method to concentrate enteric viruses from wastewater', *Journal of virological methods,* 237, pp. 150-153 Available at: 10.1016/j.jviromet.2016.09.010.

Qudeiri, J.E.A., Zaiout, A., Mourad, A.I., Abidi, M.H. and Elkaseer, A. (2020) 'Principles and Characteristics of Different EDM Processes in Machining Tool and Die Steels', *Applied Sciences,* 10(6), pp. 2082 Available at: 10.3390/app10062082.

Ramakrishnan, R. and Karunamoorthy, L. (2008) 'Modeling and multi-response optimization of Inconel 718 on machining of CNC WEDM process', *Journal of materials processing technology,* 207(1), pp. 343-349 Available at: 10.1016/j.jmatprotec.2008.06.040.

Renner, G., Schmidt, T.C. and Schram, J. (2018) 'Analytical methodologies for monitoring micro(nano)plastics: Which are fit for purpose?', *Current opinion in environmental science & health,* 1, pp. 55-61 Available at: 10.1016/j.coesh.2017.11.001.

Rickwood, D. and Graham, J. (2015) 'Centrifugation Techniques ', Available at: https://doi.org/10.1002/9780470015902.a0002704.pub2.

Rockström, J., Gaffney, O., Rogelj, J., Meinshausen, M., Nakicenovic, N. and Schellnhuber, H.J. (2017) 'A roadmap for rapid decarbonization', *Science (American Association for the Advancement of Science),* 355(6331), pp. 1269-1271 Available at: 10.1126/science.aah3443.

Sabarinathan, P., Annamalai, V.E., Kumar, S.S. and Xavier Kennedy, A. (2019) 'A study on recovery of alumina grains from spent vitrified grinding wheel', *Journal of material cycles and waste management,* 21(1), pp. 156-165 Available at: 10.1007/s10163-018-0776-8.

Sabarinathan, P., Annamalai, V.E. and Rajkumar, K. (2020) 'Sustainable application of grinding wheel waste as abrasive for abrasive water jet machining process', *Journal of cleaner production,* 261, pp. 121225 Available at: 10.1016/j.jclepro.2020.121225.

Sadowski, M., Perkins, L. and McGarvey, E. (2021) 'Roadmap to Net Zero: Delivering Science-Based Targets in the Apparel Sector', *World Resources Institute,* Available at: 10.46830/wriwp.20.00004.

Salah, G.M.J.A. and Romanova, A. (2021) 'Life cycle assessment of felt system living green wall: Cradle to grave case study', *Environmental Challenges,* 3, pp. 100046 Available at: 10.1016/j.envc.2021.100046.

Saleem, P. (2021) 'The Spectrophotometric Determination of Chromium (vi) Using N, N-diethyl-p-phenylenediamine in Synthetically Prepared Wastewater, And Tap Water', *The Journal of the University of Duhok,* 24(1), pp. 46-53 Available at: 10.26682/sjuod.2021.24.1.7.

Sanchez-Hachair, A. and Hofmann, A. (2018) 'Hexavalent chromium quantification in solution: Comparing direct UV–visible spectrometry with 1,5-diphenylcarbazide colorimetry', *Comptes rendus. Chimie,* 21(9), pp. 890-896 Available at: 10.1016/j.crci.2018.05.002.

Sandelowski, M. (2010) 'What's in a name? Qualitative description revisited', *Research in nursing & health,* 33(1), pp. 77-84 Available at: 10.1002/nur.20362.

Santiasih, I. and Ratriwardhani, R.A. (2021) 'Human error probability analysis using Success Likelihood Index Method (SLIM) approach in grinding activities', *IOP conference series. Materials Science and Engineering,* 1072(1), pp. 12027 Available at: 10.1088/1757-899X/1072/1/012027.

Sauve, G. and Van Acker, K. (2020) 'The environmental impacts of municipal solid waste landfills in Europe: A life cycle assessment of proper reference cases to support decision making', *Journal of environmental management,* 261, pp. 110216 Available at: 10.1016/j.jenvman.2020.110216.

Scatiggio, F., Breda, E., Calcara, L., Campi, G., Parodi, L., Pedriali, R., Pompili, M. and Santoro, A. (2020) *LCA and Smoke Test of Dielectric Fluids Based on Natural Esters.* IEEE, pp. 321.

Schwartz, S. (1977) 'Normative Influences on Altruism', *Advances in experimental social psychology,* 10, pp. 222.

Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., von Gunten, U. and Wehrli, B. (2010) 'Global Water Pollution and Human Health', *Annual Review of Environment and Resources,* 35(1), pp. 109-136 Available at: 10.1146/annurev-environ-100809-125342.

Sharma, P., Singh, S.P., Parakh, S.K. and Tong, Y.W. (2022) 'Health hazards of hexavalent chromium (Cr (VI)) and its microbial reduction', *Bioengineered,* 13(3), pp. 4923-4938 Available at: 10.1080/21655979.2022.2037273.

Shi, Y., Zhou, Y., Wang, Y., Chen, Y., Yan, C., Wu, J. and Yu, S. (2021) *Materials for Additive Manufacturing.* Academic Press.

Shokouhi, S., Sohrabi, M.R. and Mofavvaz, S. (2020) 'Comparison between UV/Vis spectrophotometry based on intelligent systems and HPLC methods for simultaneous determination of anti-diabetic drugs in binary mixture', *Optik (Stuttgart),* 206, pp. 164304 Available at: 10.1016/j.ijleo.2020.164304.

Shrimali, G. (2022) 'Scope 3 Emissions: Measurement and Management', *The journal of impact and ESG investing (Online),* 3(1), pp. 31-54 Available at: 10.3905/jesg.2022.1.051.

SimaPro (2020). "SimaPro Database Manual Methods Library", pg 3 – 5. Available at: https://simapro.com/wp-content/uploads/2020/06/DatabaseManualMethods.pdf.

Singh, A.K., Mahajan, R., Tiwari, A., Kumar, D. and Ghadai, R.K. (2018) 'Effect of Dielectric on Electrical Discharge Machining: A Review', *IOP conference series. Materials Science and Engineering,* 377(1), pp. 12184 Available at: 10.1088/1757-899X/377/1/012184.

Singh and Patidar, S.K. (2018) 'Microalgae harvesting techniques: A review', *Journal of environmental management,* 217, pp. 499-508 Available at: 10.1016/j.jenvman.2018.04.010.

Siva Rama Krishna, L. and Srikanth, P.J. (2021) 'Evaluation of environmental impact of additive and subtractive manufacturing processes for sustainable manufacturing', *Materials today : proceedings*, 45, pp. 3054-3060 Available at: 10.1016/j.matpr.2020.12.060.

Smith, A. (1976) *An inquiry into the nature and causes of the wealth of nations.* Chicago: Univ. of Chicago Press.

Souza, A.M. and da Silva, E.J. (2019) 'Global strategy of grinding wheel performance evaluation applied to grinding of superalloys', *Precision engineering,* 57, pp. 113-126 Available at: 10.1016/j.precisioneng.2019.03.013.

Spangenberg, M., Bryant, J.I., Gibson, S.J., Mousley, P.J., Ramachers, Y. and Bell, G.R. (2021) 'Ultraviolet absorption of contaminants in water', *Scientific reports,* 11(1), pp. 3682 Available at: 10.1038/s41598-021-83322-w.

Steinmetz, H., Knappstein, M., Ajzen, I., Schmidt, P. and Kabst, R. (2016) 'How Effective are Behavior Change Interventions Based on the Theory of Planned Behavior?', *Zeitschrift für Psychologie,* 224(3), pp. 216-233 Available at: 10.1027/2151-2604/a000255.

Stocké, V. (2019) 'The rational choice paradigm in the sociology of education'*Research Handbook on the Sociology of Education* Edward Elgar Publishing, pp. 57-68.

Sun, H., Brocato, J. and Costa, M. (2015) 'Oral Chromium Exposure and Toxicity', *Current environmental health reports,* 2(3), pp. 295-303 Available at: 10.1007/s40572-015-0054-z.

Szabo, H.M. and Tuhkanen, T. (2016) *UV/VIS spectroscopy as a method to characterize well water quality. [UV/VIS-spektroskopi som metod att karakterisera brunnsvattenkvalité]* Föreningen Vatten.

Tang, W., Zhao, T., Dou, R. and Wang, L. (2022) 'Additive manufacturing of low-shrinkage alumina cores for single-crystal nickel-based superalloy turbine blade casting', *Ceramics international,* 48(11), pp. 15218-15226 Available at: 10.1016/j.ceramint.2022.02.052.

Taniguchi, N. (1983) 'Current Status in, and Future Trends of, Ultraprecision Machining and Ultrafine Materials Processing', *CIRP annals,* 32(2), pp. 573-582 Available at: 10.1016/S0007-8506(07)60185-1.

Teigiserova, D.A., Hamelin, L. and Thomsen, M. (2020) 'Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy', *The Science of the total environment,* 706, pp. 136033 Available at: 10.1016/j.scitotenv.2019.136033.

Teng, Y., Wu, K. and Liu, H. (2015) 'Integrating Altruism and the Theory of Planned Behavior to Predict Patronage Intention of a Green Hotel', *Journal of hospitality & tourism research (Washington, D.C.),* 39(3), pp. 299-315 Available at: 10.1177/1096348012471383.

Thiounn, T. and Smith, R.C. (2020) 'Advances and approaches for chemical recycling of plastic waste', *Journal of polymer science (2020),* 58(10), pp. 1347-1364 Available at: 10.1002/pol.20190261.

Tong, K., Canadell, J.G., Jackson, R.B., Stokes, E.(., Dhakal, S., Finch, M., Jittrapirom, P., Singh, N., Yamagata, Y., Yewdall, E., Yona, L. and Seto, K.C. (2021) 'Carbon Analytics for Net-zero Emissions Sustainable Cities', *Nature sustainability,* 4(6), pp. 460-463 Available at: 10.1038/s41893-021-00715-5.

Torres-Carrillo, S., Siller, H.R., Vila, C., López, C. and Rodríguez, C.A. (2020) 'Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades', *Journal of cleaner production,* 246, pp. 119068 Available at: 10.1016/j.jclepro.2019.119068.

Tortora, F., Innocenzi, V., Prisciandaro, M., Vegliò, F. and Mazziotti di Celso, G. (2016) 'Heavy Metal Removal from Liquid Wastes by Using Micellar-Enhanced Ultrafiltration', *Water, air, and soil pollution,* 227(7), pp. 1 Available at: 10.1007/s11270-016-2935-7.

UK Government (2019) *The Climate Change Act 2008 (2050 Target Amendment) Order 2019.* . Available at: https://www.legislation.gov.uk/uksi/2019/1056/contents/made (Accessed: July 2022).

United Nations (2015) *Paris Agreement.* Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (Accessed: November 2022).

Urpelainen, J. (2017) 'The limits of carbon reduction roadmaps', *Science (American Association for the Advancement of Science),* 356(6342), pp. 1019 Available at: 10.1126/science.aan6266.

Valaki, J.B., Rathod, P.P. and Sidpara, A.M. (2018) 'Sustainability Issues in Electric Discharge Machining'*Innovations in Manufacturing for Sustainability* Cham: Springer International Publishing, pp. 53-75.

Vining, J. and Ebreo, A. (1992) 'Predicting Recycling Behavior from Global and Specific Environmental Attitudes and Changes in Recycling Opportunities', *Journal of applied social psychology,* 22(20), pp. 1580-1607 Available at: 10.1111/j.1559-1816.1992.tb01758.x.

Wagner, J., Wang, Z., Ghosal, S., Rochman, C., Gassel, M. and Wall, S. (2017) 'Novel method for the extraction and identification of microplastics in ocean trawl and fish gut matrices', *Analytical methods,* 9(9), pp. 1479-149 Available at: 10.1039/c6ay02396g.

Wang, H., Sikora, P., Rutgersson, C., Lindh, M., Brodin, T., Björlenius, B., Larsson, D.G.J. and Norder, H. (2018) 'Differential removal of human pathogenic viruses from sewage by conventional and ozone treatments', *International Journal of Hygiene and Environmental Health,* 221(3), pp. 479-488 Available at: 10.1016/j.ijheh.2018.01.012.

Wang, X. and Shen, Y. (2019) 'High-speed EDM milling with in-gas and outside-liquid electrode flushing techniques', *International journal of advanced manufacturing technology,* 104(5-8), pp. 3191-3198 Available at: 10.1007/s00170-019-04242-8.

Wang, Y. and Jing, X. (2005) 'Effect of solution concentration on the UV–vis spectroscopy measured oxidation state of polyaniline base', *Polymer testing,* 24(2), pp. 153-156 Available at: 10.1016/j.polymertesting.2004.09.013.

Wang, Y., Xue, Y. and Zhang, C. (2021) 'Electrochemical product engineering towards sustainable recovery and manufacturing of critical metals', *Green chemistry : an international journal and green chemistry resource : GC,* 23(17), pp. 631-6321 Available at: 10.1039/d1gc01462e.

Watson, J.K. and Taminger, K.M.B. (2018) 'A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption', *Journal of cleaner production,* 176, pp. 1316-1322 Available at: 10.1016/j.jclepro.2015.12.009.

Widiatami, A.K., Pitaloka, L.K. and Nurkhin, A. (2022) 'Environmental management system: The internal and external impact of ISO 14001 implementation on the manufacturing companies', *IOP Conference Series: Earth and Environmental Science,* 1098(1), pp. 12001 Available at: 10.1088/1755-1315/1098/1/012001.

Yadav, A., Singh, Y., Singh, S. and Negi, P. (2021) 'Sustainability of vegetable oil based bio-diesel as dielectric fluid during EDM process – A review', *Materials today : proceedings,* 46, pp. 11155-11158 Available at: 10.1016/j.matpr.2021.01.967.

Yadav, V.K., Kumar, P. and Dvivedi, A. (2019) 'Performance enhancement of rotary tool near-dry EDM of HSS by supplying oxygen gas in the dielectric medium', *Materials and manufacturing processes,* 34(16), pp. 1832-1846 Available at: 10.1080/10426914.2019.1675889.

Yang, F., Bellotti, M., Hua, H., Yang, J., Qian, J. and Reynaerts, D. (2018) 'Experimental analysis of normal spark discharge voltage and current with a RC-type generator in micro-EDM', *International journal of advanced manufacturing technology,* 96(5-8), pp. 2963-2972 Available at: 10.1007/s00170-018-1813-4.

Yao, L., Zhou, W., Wang, T., Liu, M. and Yu, C. (2014) 'Quantification of egg yolk contamination in egg white using UV/Vis spectroscopy: Prediction model development and analysis', *Food control,* 43, pp. 88-97 Available at: 10.1016/j.foodcont.2014.02.037.

Yueqin, Z., Zhidong, L., Hongwei, P. and Mingbo, Q. (2017) 'Dielectric fluid lifespan detection based on pulse discharge probability in wire electrical discharge machining', *International journal of* *advanced manufacturing technology,* 92(1-4), pp. 1481-1491 Available at: 10.1007/s00170-017-0211-7.

Yuriev, A., Dahmen, M., Paillé, P., Boiral, O. and Guillaumie, L. (2020) 'Pro-environmental behaviors through the lens of the theory of planned behavior: A scoping review', *Resources, conservation and recycling,* 155, pp. 104660 Available at: 10.1016/j.resconrec.2019.104660.

Zey, M.A. (2015) *Rational Choice and Organization Theory.* Second Edition edn.Elsevier Ltd.

Zhang, Y., Gu, L. and Guo, X. (2020) 'Carbon audit evaluation system and its application in the iron and steel enterprises in China', *Journal of cleaner production*, 248, pp. 119204 Available at: 10.1016/j.jclepro.2019.119204.

Zhang, Z., Yan, J. and Kuriyagawa, T. (2019) 'Manufacturing technologies toward extreme precision', *International Journal of Extreme Manufacturing,* 1(2), pp. 22001 Available at: 10.1088/2631-7990/ab1ff1.

Zhang, Hu, M., Di Maio, F., Sprecher, B., Yang, X. and Tukker, A. (2022) 'An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe', *The Science of the total environment,* 803, pp. 149892 Available at: 10.1016/j.scitotenv.2021.149892.

Zhou, Y., Zhang, B., Zou, J., Bi, J. and Wang, K. (2012) 'Joint R&D in low-carbon technology development in China: A case study of the wind-turbine manufacturing industry', *Energy policy,* 46(1), pp. 100-108 Available at: 10.1016/j.enpol.2012.03.037.

Zhou, Z., Lu, T., Sun, S. and Wang, Q. (2023) 'Roles and gains of coordination chemistry in nanofiltration membrane: A review', *Chemosphere (Oxford),* 318, pp. 137930 Available at: 10.1016/j.chemosphere.2023.137930.

12.0 APPENDIX

Appendices 12.1 Example grinding wheel monitoring sheet (blank)

Machine: ________					
Job	***Grinding Wheel Manufacturer***	***Grinding Wheel Dimensions***	***New Grinding Wheel (Yes / No)***	***Date***	***Time***

Appendices 12.2 Questionnaire answer selection rates

Question: "What are your reasons for changing a grinding wheel?"

This question was answered by 17 out of 19 questionnaire respondents, resulting in a response rate of 89.47%. Respondents chose from 6 options with no limit to how many of these options could be selected. From the 6 options "*The minimum diameter of the grinding wheel has been reached*" was ranked highest, with 76.47% of respondents selecting this option. This was followed by "*The next job requires a different type/size of grinding wheel*", with a 70.59% selection rate, and then by "*Job has been completed*", with a 58.82% selection rate.

Question: "What are the biggest barriers to storing part-worn grinding wheels after use?"

The response rate for this question was 89.47%. 8 options were available to respondents with no limit on how many options could be selected. "*There is no re-use pile*" was ranked highest with 82.35% selection rate. "*The wheel has reached its minimum diameter*" was ranked second with a 64.71% selection rate. The third ranked option was "*The wheel is close to its minimum diameter*", with a selection rate of 41.18%.

Question: "What are the biggest barriers to using part-worn grinding wheels?"

This question had a response rate of 89.47%. 10 options were available to respondents with no limit on how many options could be selected. The highest ranked option was "*There is no re-use pile*", with a selection rate of 82.35. "*They would require measuring before use*" was ranked second highest, with a selection rate of 64.71%. Following this "*There are no barriers to using a wheel from the re-use pile*" was ranked third highest with 17.65% selection rate.

Question: "What are the biggest barriers to a sustainable grinding process?"

This question had a response rate of 89.47%. 7 options were available to respondents with no limit on how many options could be selected. The highest ranked barrier was "*Insufficient sustainability* *training*" with a 64.71% selection rate, followed by "*Viable grinding wheels being wasted*" with a 58.82% selection rate, and then "*Energy waste from inefficient machines*" with a 35.29% selection rate.

Appendices 12.3 Cross-tabulation results

When examining the correlation between an operator's employment length and their ability to fit a part-worn grinding wheel onto a machine it became apparent that operators with a 'long' employment length were capable of doing this action. When categorising employment length, less than 5 years was considered 'short', between 5 years 1 month and 10 years was considered 'medium', and greater than 10 years 1 month was considered 'long'. All 7 employees with a 'long' employment duration claimed to be capable of fitting a part-worn grinding wheel.

Additionally, a correlation between training frequency and if the employee had been taught the usable lifespan of grinding wheels was apparent, with 8 out of the 11 operators that said training was only received *at the beginning of employment* also saying that the training did not cover grinding wheel lifespan.

Finally, there was correlation between *barriers to storing part-worn wheels* and *barriers to using part-worn wheels*. 5 out of 6 operators who felt *there is no re-use pile* was a barrier to storing part-worn wheels also felt that this was a barrier to using part-worn wheels.

Appendices 12.4 UV-Vis statistical analysis

Multiple Comparisons

Dependent Variable: Absorbance

Tukey HSD

(I) SampleCondition	(J) SampleCondition	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Untreated	Untreated (Diluted)	1.665000*	.023551	<.001	1.58589	1.74411
	Filtered	1.681000*	.023551	<.001	1.60189	1.76011
	Centrifuged	2.438000*	.023551	<.001	2.35889	2.51711
	Filtered and Centrifuged	2.459000*	.023551	<.001	2.37989	2.53811
	Clean	3.279000*	.023551	<.001	3.19989	3.35811
Untreated (Diluted)	Untreated	-1.665000*	.023551	<.001	-1.74411	-1.58589
	Filtered	.016000	.023551	.981	-.06311	.09511
	Centrifuged	.773000*	.023551	<.001	.69389	.85211
	Filtered and Centrifuged	.794000*	.023551	<.001	.71489	.87311
	Clean	1.614000*	.023551	<.001	1.53489	1.69311
Filtered	Untreated	-1.681000*	.023551	<.001	-1.76011	-1.60189
	Untreated (Diluted)	-.016000	.023551	.981	-.09511	.06311
	Centrifuged	.757000*	.023551	<.001	.67789	.83611
	Filtered and Centrifuged	.778000*	.023551	<.001	.69889	.85711
	Clean	1.598000*	.023551	<.001	1.51889	1.67711
Centrifuged	Untreated	-2.438000*	.023551	<.001	-2.51711	-2.35889
	Untreated (Diluted)	-.773000*	.023551	<.001	-.85211	-.69389
	Filtered	-.757000*	.023551	<.001	-.83611	-.67789
	Filtered and Centrifuged	.021000	.023551	.941	-.05811	.10011
	Clean	.841000*	.023551	<.001	.76189	.92011
Filtered and Centrifuged	Untreated	-2.459000*	.023551	<.001	-2.53811	-2.37989
	Untreated (Diluted)	-.794000*	.023551	<.001	-.87311	-.71489
	Filtered	-.778000*	.023551	<.001	-.85711	-.69889
	Centrifuged	-.021000	.023551	.941	-.10011	.05811
	Clean	.820000*	.023551	<.001	.74089	.89911
Clean	Untreated	-3.279000*	.023551	<.001	-3.35811	-3.19989
	Untreated (Diluted)	-1.614000*	.023551	<.001	-1.69311	-1.53489
	Filtered	-1.598000*	.023551	<.001	-1.67711	-1.51889
	Centrifuged	-.841000*	.023551	<.001	-.92011	-.76189
	Filtered and Centrifuged	-.820000*	.023551	<.001	-.89911	-.74089

*. The mean difference is significant at the 0.05 level.

Appendices 12.5 GC-MS results

Compound	**Retention Time**					
	Untreated	*Filtered*	*Centrifuged*	*Filtered and centrifuged*	*Clean*	*Average*
n-tetradecane	18.61	18.56	18.54	18.54	18.59	18.57
2(1H)-Natphthalenone	19.53	19.46	19.45	19.44	19.49	19.47
1,54-dibromotetrapentacontane	20.49	20.26	20.42	20.22	20.48	20.37
9-n-hexylheptadecane	27.65	27.63	27.6	27.53	27.63	27.61
2,3-dimethylheptadecane	27.82	27.82	27.77	27.71	27.8	27.78
n-octadecane	28.48	28.48	28.44	28.36	28.47	28.45
n-nonadecane	30.58	30.56	30.53	30.49	30.57	30.55
17-Pentatriacontene	31.41	31.36	31.35	31.32	31.39	31.37
n,n-diethylbiphenyl-4-amine	31.94	31.9	31.89	31.86	31.94	31.91
n-eicosane	32.6	32.56	32.55	32.52	32.59	32.56
n-heneicosane	34.55	34.5	34.48	34.47	34.54	34.51
n-docosane	36.42	36.36	36.35	36.35	36.41	36.38
tert-octyldiphenylamine	38.13	38.08	38.06	38.05	38.12	38.09
4,4-di-tert-butyl-diphenylamine	38.46	38.4	38.39	38.38	38.45	38.42

Appendices 12.6 Grinding Operator Questionnaire

ELE Advanced Technologies: Grinding Operator Questionnaire

Start of Block: Consent Form

Information Sheet **Participant Information Sheet**

1. Title of Study

Reducing waste within the high precision manufacturing industry to achieve Net Zero and sustainability targets. Case study: ELE Advanced Technologies.

2. Version Number and Date

Information sheet version 2.0.

February, 2023.

3. Invitation Paragraph

You are invited to participate in a questionnaire-based study regarding the material waste generated by ELE Advanced Technologies, specifically during the Grinding process. Before you decide to participate, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and feel free to ask us if you would like more information or if there is anything you do not understand. We would like to stress that you do not have to accept this invitation and should only agree to take part if you want to. The questionnaire should take approximately 10-15 minutes to complete.

4. What is the purpose of the study?

The purpose of this study if to identify any barriers that prevent the Grinding process from being environmentally sustainable. This information will be fed back to management teams within the company to inform any required changes to the grinding process that reduce the amount of waste being generated, increasing the environmental sustainability of ELE Advanced Technologies.

5. Why have I been invited to take part?

You have been chosen to participate in this research due to being a grinding machine operator at ELE Advanced Technologies, therefore, you will help provide valuable insights into the requirements of the Grinding process. All grinding machine operators across all three sites of ELE Advanced Technologies will be recruited for this research.

6. Do I have to take part?

Your participation in this study is entirely voluntary. You may refuse to take part in the research and decline to answer any questions you do not wish to answer without penalty. You can withdraw from the research and up to 4 weeks after submitting the questionnaire. All your data will be erased from our systems. To withdraw, please email the student researcher (lollerenshaw1@uclan.ac.uk) or principle researcher (kswilliams@uclan.ac.uk) with your request to be removed from the research and your unique questionnaire code (provided at the end of this document) and your request will be facilitated.

7. What will happen if I take part?

You will be required to complete a questionnaire that is designed to assess the sustainability of the Grinding process. Some questions will ask about your behaviours in specific scenarios experienced during the Grinding process, while other questions will focus on the training that ELE Advanced Technologies may have provided. Your only responsibility is to answer the questions as honestly as possible and to complete the questionnaire within two weeks of receiving it; all responses are anonymised, and individual questionnaires will only be seen by the student investigator.

Questionnaires will be distributed using two methods, physical copies of the questionnaire will be available in the break room at your site with a locked box provided for completed questionnaires to be placed. This box will be collected by the student researcher at the end of each day for two weeks after being placed in the break room. Online copies of the questionnaire will be distributed via email from your floor manager. The email will contain a link to the online questionnaire, which can be completed on your laptop or your phone. You may complete either an online or physical copy depending on ease, it is not necessary to complete both an online and physical copy as they are identical questions. Your line manager will not see who has completed the questionnaires.

Please only complete one version of the questionnaire, there is no requirement to complete a physical and online copy.

Data from the questionnaires will only be handled by the student investigator conducting the research.

Please return completed questionnaires within two weeks of the questionnaire being provided.

8. How will my data be used?

The University processes personal data as part of its research and teaching activities in accordance with the lawful basis of 'public task', and in accordance with the University's purpose of "advancing education, learning and research for the public benefit". Under UK data protection legislation, the University acts as the Data Controller for personal data collected as part of the University's research.

The University privacy notice for research participants can be found on the attached link:https://www.uclan.ac.uk/data_protection/privacy-notice-research-participants.php

9. Are there any risks in taking part?

There are no foreseeable risks involved in participating in this study and the answers you provide within this questionnaire will have no impact on your role at ELE Advanced Technologies.

All personal data being collected in this questionnaire will be anonymised before the data is processed. No identifiable data will be published, and all completed questionnaires will be securely stored at The University of Central Lancashire. Once your provided data has been processed, your completed questionnaire will be disposed of in the appropriate manner. These steps are to protect all data that you provide.

10. Are there any benefits from taking part?

You will receive no direct benefits from participating in this research. However, your responses may help to minimise the negative environmental effects caused by ELE Advanced Technologies. The information obtained and conclusions will be made available through the company newsletter.

11. Expenses and / or payments

No expenses or payment requirements will be incurred by participating in this study.

12. What will happen to the results of the study?

Results of this study will be used for a research thesis and a business report for ELE Advanced Technologies, which will highlight any barriers to sustainable grinding and identify ways of reducing waste output from the grinding process. All findings will be made available to research participants via the ELE Advanced Technologies newsletter.

13. What will happen if I want to stop taking part?

Participation in this project is voluntary, and you can withdraw at any time without giving a reason. To withdraw, please email the student researcher (lollerenshaw1@uclan.ac.uk) or principle researcher (kswilliams@uclan.ac.uk) with your request to be removed from the research and your unique questionnaire code (provided at the end of this document) and your request will be facilitated. If you wish to withdraw, please note that data already collected can only be withdrawn up to 4 weeks after the questionnaire has been completed. After this point, the researcher will have combined the data and your information will have been anonymised ready for analysing and it won't be possible to identify who you are.

14. What if I am unhappy or if there is a problem?

If you are unhappy, or if there is a problem, please feel free to let us know by contacting Karl Williams and we will try to help. If you remain unhappy or have a complaint which you feel you cannot come to us with, then please contact the Ethics, Integrity and Governance Unit at OfficerForEthics@uclan.ac.uk.

The University strives to maintain the highest standards of rigour in the processing of your data. However, if you have any concerns about the way in which the University processes your personal data, it is important that you are aware of your right to lodge a complaint with the Information Commissioner's Office by calling 0303 123 1113

15. Who can I contact if I have further questions?

Please contact the principal investigator, Karl Williams on +44 (0) 1772 893496 or kswilliams@uclan.ac.uk

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Q88 **Participant Consent Form**

1. I confirm that I have read and have understood the information sheet dated 18/12/2022 for the above study, or it has been read to me. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2. I understand that taking part in the study involves completing a questionnaire, either a physical or online copy.

3. I understand that my participation is voluntary and that I am free to stop taking part and can withdraw from the study at any time without giving any reason and without my rights being affected. In addition, I understand that I am free to decline to answer any particular question or questions.

4. I understand that I can ask for access to the information I provide, and I can request the destruction of that information if I wish at any time prior to 4-weeks after submitting the questionnaire. I understand that following these 4-weeks I will no longer be able to request access to or withdrawal of the information I provide.

5. I understand that the information I provide will be held securely and in line with data protection requirements at the University of Central Lancashire.

6. I understand that signed consent forms and questionnaires will be securely retained for up to 7 years as per the university requirements.

Q89 **Participant agreement**

○ Please select to confirm you have read and understood the 'participation information sheet' and the 'participant consent form' and that you agree to take part in the above investigation. (1)

Unique ID **Your unique questionnaire ID is: ${e://Field/Survey%20ID}**

End of Block: Consent Form

Start of Block: Section 1: Grouping information

Q1 What is your main site of operation?

○ Cotton Tree Lane, Colne (1)

○ Skipton Road, Colne (2)

○ Churchill Way, Nelson (3)

Q2 How long have you worked at ELE Advanced Technologies?

○ Years (1) ____

○ Months (2) ____

Q3 Please tick how frequently you perform the following types of grinding.

	Never (1)	Rarely (2)	Sometimes (3)	Often (4)	Always (5)
Viper Grinding (1)	○	○	○	○	○
Creep Feed Grinding (2)	○	○	○	○	○
Reciprocating Grinding (3)	○	○	○	○	○

Q4 Does the type of grinding you perform affect how you dispose of grinding wheels?

- ◯ Yes (1)
- ◯ No (2)

Display This Question:

If Does the type of grinding you perform affect how you dispose of grinding wheels? = Yes

Q5 Please explain how and why the type of grinding performed affects disposal of grinding wheels.

____

Page Break

End of Block: Section 1: Grouping information

Start of Block: Section 2: Grinding and Wheel Use

Q1 Do you regularly monitor the number of wheel changes you perform during the grinding process?

◯ Yes (1)

◯ No (2)

Display This Question:

If Do you regularly monitor the number of wheel changes you perform during the grinding process? = Yes

Q1.i How many grinding wheels do you change each month on average?

◯ 1 - 10 (1)

◯ 11 - 20 (2)

◯ 21 - 30 (3)

◯ 31 - 40 (4)

◯ 41 - 50 (5)

◯ 51 - 60 (6)

◯ 61+ (7)

Q2 What factors determine when you change a grinding wheel? (Please select all that apply)

- ☐ The next job requires a different type/size of grinding wheel. (1)
- ☐ The minimum diameter of the grinding wheel has been reached. (2)
- ☐ The finish quality of the product is decreasing. (3)
- ☐ The speed at which the wheel is completing the job has slowed. (4)
- ☐ Status of the job (i.e. once completed, the wheel is removed from the machine). (5)
- ☐ None of these factors. (6)

Display This Question:

If What factors determine when you change a grinding wheel? (Please select all that apply) != None of these factors.

Carry Forward Selected Choices from "What factors determine when you change a grinding wheel? (Please select all that apply)"

X→

Q2.a Please rank the most important factors that determine when you change a grinding wheel, from most to least.

_______ The next job requires a different type/size of grinding wheel. (1)
_______ The minimum diameter of the grinding wheel has been reached. (2)
_______ The finish quality of the product is decreasing. (3)
_______ The speed at which the wheel is completing the job has slowed. (4)
_______ Status of the job (i.e. once completed, the wheel is removed from the machine). (5)
_______ None of these factors. (6)

Q3 Do you regularly put used grinding wheels in the re-use pile?

○ Yes (1)

○ No (2)

Display This Question:

If Do you regularly put used grinding wheels in the re-use pile? = Yes

Q3.i When do you put wheels in the re-use pile? (Please select all that apply)

☐ Whenever the minimum diameter has not been reached and the wheel has only been used once. (1)

☐ Whenever the minimum diameter not been reached, even if the wheel has been used two or more times. (2)

☐ Whenever the minimum diameter of a wheel has been reached. (3)

☐ When a new job is started, any wheel previously on the machine is placed into the re-use pile. (6)

☐ Whenever a wheel has performed a specific number of runs (this may vary between wheels) it is removed and placed onto the re-use pile. (4)

☐ Whenever the wrong wheel was used for a job, it is removed and placed onto the re-use pile. (5)

☐ At the end of each shift, all wheels are removed from grinding machines and placed into the re-use pile. (7)

☐ Whenever a removed wheel is far from reaching its minimum diameter and the wheel has only been used once. (8)

☐ Whenever a removed wheel is far from reaching its minimum diameter, even if the wheel has been used two or more times. (9)

Display This Question:

If Do you regularly put used grinding wheels in the re-use pile? = Yes

Q3.ii How do you record the remaining wheel diameter when placing a used grinding wheel into the re-use pile? (Please select all that apply)

- ☐ By writing the diameter on the used wheel. (1)
- ☐ By writing a label and attaching it to the used wheel. (2)
- ☐ By completing a monitoring sheet that is by the grinding machine. (3)
- ☐ By entering the remaining diameter into a computer spreadsheet. (4)
- ☐ By telling other grinding operators how much diameter is remaining. (5)
- ☐ I do not record it because I do not know the remaining diameter. (6)
- ☐ I do not record it because there is not a suitable recording system. (7)

Display This Question:

If How do you record the remaining wheel diameter when placing a used grinding wheel into the re-use... = I do not record it because there is not a suitable recording system.

Q3.ii.a Please specify which options from the previous question would be your preferred recording system and explain why this is your choice. The options are listed below:

a) By writing the diameter on the used wheel.

b) By writing a label and attaching it to the used wheel.

c) By completing a monitoring sheet that is by the grinding machine.

d) By entering the remaining diameter into a computer spreadsheet.

e) By telling other grinding operators how much diameter is remaining.

____

Q4 What are the barriers to putting used wheels into the re-use pile? (Please select all that apply)

- ▢ It is not specified in the standard operating procedure (S.O.P) (4)
- ▢ There is no re-use pile. (7)
- ▢ The wheel has reached its minimum diameter. (3)
- ▢ The wheel is close to its minimum diameter. (2)
- ▢ The wheel had already been in the re-use pile. (1)
- ▢ It would require recording the wheels remaining diameter. (5)
- ▢ It would be unnecessary as the re-use pile is never used. (6)
- ▢ There are no barriers to putting a used wheel in the re-use pile. (8)

Display This Question:

If What are the barriers to putting used wheels into the re-use pile? (Please select all that apply) != There are no barriers to putting a used wheel in the re-use pile.

Carry Forward Selected Choices from "What are the barriers to putting used wheels into the re-use pile? (Please select all that apply)"

Q4.a Please rank the most important barriers to putting used wheels into the re-use pile, from most to least.

_______ It is not specified in the standard operating procedure (S.O.P) (1)
_______ There is no re-use pile. (2)
_______ The wheel has reached its minimum diameter. (3)
_______ The wheel is close to its minimum diameter. (4)
_______ The wheel had already been in the re-use pile. (5)
_______ It would require recording the wheels remaining diameter. (6)
_______ It would be unnecessary as the re-use pile is never used. (7)
_______ There are no barriers to putting a used wheel in the re-use pile. (8)

Q5 Do you use grinding wheels from the re-use pile?

○ Yes (1)

○ No (2)

Display This Question:

If Do you use grinding wheels from the re-use pile? = Yes

Q5.i When selecting a wheel from the re-use pile, what criteria must be met? (Please select all that apply)

☐ The wheel must have been used only once before. (1)

☐ The wheel must have its current remaining diameter clearly recorded. (2)

☐ The wheel must be easily accessible. (3)

☐ The wheel must not have reached its minimum diameter (4)

☐ The wheel must be far from its minimum diameter. (5)

Display This Question:

If Do you use grinding wheels from the re-use pile? = Yes

Q5.ii When do you use a grinding wheel from the re-use pile? (Please select all that apply)

- ▢ When the wheel in the re-use pile has a large diameter remaining (3)
- ▢ When the wheel in the re-use pile is close to its minimum diameter (4)
- ▢ When a small number of runs need to be completed. (5)
- ▢ When a large number of runs need to be completed. (6)
- ▢ Every time I need to change a wheel. (1)
- ▢ Every time I start a new job. (2)
- ▢ When it is the first job of the day. (7)
- ▢ When it is the last job of the day. (8)
- ▢ When I have done a specific number of wheel changes (please specify) (9) ____

Q6 What are the barriers to using wheels from the re-use pile? (Please select all that apply)

- ▢ It is not specified in the Standard Operating Procedure (S.O.P) (9)
- ▢ There is no re-use pile (10)
- ▢ They are harder to fit onto the machine. (7)
- ▢ Their dimensions are not clearly labelled. (3)
- ▢ They would require measuring before use. (5)
- ▢ They are inadequately stored. (1)
- ▢ They are in an inconvenient location. (2)
- ▢ They will not grind as effectively as a new wheel. (4)
- ▢ It is unclear how many runs they will be able to achieve. (6)
- ▢ There are no barriers to using a wheel from the re-use pile. (8)

Display This Question:

If What are the barriers to using wheels from the re-use pile? (Please select all that apply) != There are no barriers to using a wheel from the re-use pile.

Carry Forward Selected Choices from "What are the barriers to using wheels from the re-use pile? (Please select all that apply)"

X→

Q6.i Please rank the most important barriers to using wheels from the re-use pile, most to least.

_______ It is not specified in the Standard Operating Procedure (S.O.P) (1)
_______ There is no re-use pile (2)
_______ They are harder to fit onto the machine. (3)
_______ Their dimensions are not clearly labelled. (4)
_______ They would require measuring before use. (5)
_______ They are inadequately stored. (6)
_______ They are in an inconvenient location. (7)
_______ They will not grind as effectively as a new wheel. (8)
_______ It is unclear how many runs they will be able to achieve. (9)
_______ There are no barriers to using a wheel from the re-use pile. (10)

Q7 Do you know how to fit a part-worn wheel onto a grinding machine?

○ Yes (1)

○ No (2)

Display This Question:

If Do you know how to fit a part-worn wheel onto a grinding machine? = No

Q7.i What would be most useful for explaining how to fit part-worn wheels onto a grinding machine?

○ Steps described in Standard Operating Procedure (S.O.P) (1)

○ Specific training provided by ELE (2)

○ Both (Training and S.O.P) (3)

Display This Question:

If When do you put wheels in the re-use pile? (Please select all that apply) = Whenever a removed wheel is far from reaching its minimum diameter and the wheel has only been used once.

Or When do you put wheels in the re-use pile? (Please select all that apply) = Whenever a removed wheel is far from reaching its minimum diameter, even if the wheel has been used two or more times.

Or What are the barriers to putting used wheels into the re-use pile? (Please select all that apply) = The wheel is close to its minimum diameter.

Or When selecting a wheel from the re-use pile, what criteria must be met? (Please select all that a... = The wheel must be far from its minimum diameter.

Or When do you use a grinding wheel from the re-use pile? (Please select all that apply) = When the wheel in the re-use pile has a large diameter remaining

Or When do you use a grinding wheel from the re-use pile? (Please select all that apply) = When the wheel in the re-use pile is close to its minimum diameter

Q.a How do you determine if a wheel has enough remaining diameter to be re-used?

____

End of Block: Section 2: Grinding and Wheel Use

Start of Block: Section 3: Sustainability Awareness

Q1 How often does ELE provide training specific to the grinding process?

- ○ At least once a month. (1)
- ○ At least once every 6 months. (2)
- ○ At least once a year. (3)
- ○ At least once every 5 years. (4)
- ○ Only at the beginning of employment. (5)
- ○ Never. (6)

Display This Question:

If How often does ELE provide training specific to the grinding process? != Never.

Q1.i Which of the following does ELE's grinding process training cover? (Please select all that apply)

- ☐ ELE's sustainability goals. (1)
- ☐ How to fit a part-worn wheel onto the grinding machine (2)
- ☐ The usable lifespan of grinding wheels. (3)
- ☐ When to replace a grinding wheel. (4)
- ☐ Storing new grinding wheels effectively. (5)
- ☐ Storing part-worn grinding wheels effectively . (6)
- ☐ How to reduce energy use throughout the grinding process. (7)
- ☐ Operating all types of grinding machines. (8)
- ☐ Operating most types of grinding machines (please specify which are not covered) (9) ____
- ☐ Operating limited types grinding machines (please specify which are covered) (10) ____
- ☐ None of the above. (11)

Q2 Has ELE provided you with Carbon Literacy training?

- ○ Yes (1)
- ○ No (2)

Q3 What is sustainability?

____

Q4 What are the barriers for ELE’s grinding process to operate sustainably? (Please select all that apply)

- ▢ Viable grinding wheels being wasted. (2)
- ▢ Insufficient sustainability training (7)
- ▢ Lack of green/renewable energy suppliers. (5)
- ▢ Not enough recycling of grinding waste. (1)
- ▢ Energy waste from unused machines. (3)
- ▢ Energy waste from inefficient machines. (4)
- ▢ None, ELE’s grinding process is completely sustainable. (6)

Display This Question:

If What are the barriers for ELE’s grinding process to operate sustainably? (Please select all that... != None, ELE’s grinding process is completely sustainable.

Carry Forward Selected Choices from "What are the barriers for ELE’s grinding process to operate sustainably? (Please select all that apply)"

X→

Q4.i Please rank each of the barriers selected by how big of an issue they are (biggest to smallest).

_______ Viable grinding wheels being wasted. (1)
_______ Insufficient sustainability training (2)
_______ Lack of green/renewable energy suppliers. (3)
_______ Not enough recycling of grinding waste. (4)
_______ Energy waste from unused machines. (5)
_______ Energy waste from inefficient machines. (6)
_______ None, ELE’s grinding process is completely sustainable. (7)

End of Block: Section 3: Sustainability Awareness
