School of Civil and Mechanical Engineering

Eco-efficiency Performance Comparison of Additive and Subtractive Manufactured Parts

Heshan Thenuka Wijerathne Jayawardane

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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Heshan Thenuka Wijerathne Jayawardane

14.04.2023

ABSTRACT

Manufacturing industries are currently facing increased pressure to adopt cleaner production strategies to enhance their sustainability performance. This shift towards sustainability is driven by various factors, including strict environmental regulations, increased environmental and socio-economic awareness among the general public, and intensified competition in the market. Therefore, it is essential to evaluate the sustainability performance of manufactured parts using a holistic approach. Additive manufacturing has emerged as a promising technology that can produce parts with higher durability, reduced material wastage, lower energy consumption, and fewer emissions, thereby enabling manufacturers to gain a competitive advantage.

Recent studies have demonstrated that the technical feasibility assessment of additive manufactured parts is crucial prior to their sustainability performance assessment, in order to ensure that they exhibit comparable technical properties to subtractive manufactured parts. Technical feasibility assessment needs to be integrated into sustainability performance assessment, as the durability and service life of products significantly impacts sustainability performance. Whilst existing studies have primarily examined the environmental, economic, and social impacts of manufactured parts separately, there is a growing need for a comprehensive decision-support tool that integrates these three objectives of sustainability. Additionally, the social aspects of manufacturing have not been adequately evaluated in sustainability performance assessments, requiring more comprehensive assessments.

The aim of this thesis is to develop a robust decision support tool for the manufacturing industry, which facilitates the selection of cost-effective, environmentally benign, and technically feasible products. This has been achieved through the ‘techno-eco-efficiency’ framework, which provides a comprehensive assessment of the technical, economic, and environmental performance of both additive and subtractive manufactured parts. This framework integrates technical feasibility assessment, environmental life cycle assessment, life cycle costing, and eco-efficiency portfolio analysis. Additionally, the framework could serve as a platform to identify hotspots that require improvement and conduct iterative assessments for improvement strategies until the technical, environmental, social, and economic targets are met.

The technical feasibility of manufactured parts was evaluated by examining geometric properties, tensile properties, fatigue properties, build material properties, surface properties, and functional performance. The most technically feasible configurations of manufactured parts were then assessed for eco-efficiency performance. The environmental impacts of parts throughout their entire life cycle were evaluated using an environmental life cycle assessment method, whilst the economic impacts were determined using a life cycle costing approach. The life cycle environmental impacts and life cycle costs were then integrated using the eco-efficiency portfolio analysis to evaluate the eco-efficiency performance of each manufactured part.

A semi-open centrifugal pump impeller was selected as the case study to implement the techno-eco-efficiency framework for additive and subtractive manufacturing processes. The techno-eco-efficiency framework was initially implemented for virgin polymer composites and virgin metals.

A nylon composite material was used as the virgin polymer composite, and it was additive manufactured using fused filament fabrication technology. A virgin nylon material was used as the benchmark for technical feasibility and eco-efficiency assessment. Pump impellers were manufactured with different configurations of infill percentage, infill patterns and reinforcement materials. The fibre-reinforced nylon composite configuration of the pump impeller made through additive manufacturing was determined to be techno-eco-efficient in comparison to the subtractive manufactured nylon counterpart.

The techno-eco-efficiency framework was then used to assess the metallic materials using stainless steel 316L and extrusion-based additive manufacturing technology known as ‘bound metal deposition’. Stainless steel 316L bulk material was used as the benchmark for technical feasibility and eco-efficiency assessments. The stainless steel 316L pump impeller made through additive manufacturing was found to be techno-eco-efficient in comparison to subtractive manufactured stainless-steel counterparts.

The next step was to identify the environmental hotspots of manufactured parts. The material processing stage was identified as the most significant environmental hotspot, and the eco-efficiency improvement strategy of replacing virgin materials with recycled materials was considered. A pump impeller was manufactured using recycled polylactic acid material, which demonstrated very high eco-efficiency compared to the virgin polylactic acid additive manufactured part, subtractive manufactured PLA part, and formative manufactured polylactic acid part benchmarks.

Finally, the social impacts of techno-eco-efficient options identified through the techno-eco-efficiency framework were evaluated through a social life cycle assessment method. The social impacts were assessed under stakeholders of employees, local community, and society, which included the indicators of health and safety, employment level, landfill reduction, and resource conservation.

Overall, this thesis contributes to the advancement of sustainable manufacturing by providing a framework for comparing the sustainability performance of additive and subtractive manufactured parts through experiments and analysis. It was demonstrated that the techno-eco-efficiency framework could act as a decision support tool to assist manufacturers in the improvement of the sustainability performance of their manufacturing strategies.

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GLOSSARY

ABS	Acrylonitrile butadiene styrene
ADP	Abiotic depletion potential
AM	Additive Manufacturing
CED	Cumulative Energy Demand
CMM	Coordinate measuring machine
CNC	Computer numeric control
CRF	Capital recovery factor
EDM	Electro-discharge machining
EE	Eco-efficiency
EI	Environmental impact
ELCA	Environmental life cycle assessment
FFF	Fused filament fabrication
FU	Functional unit
GDEI	Gross domestic environmental impact
GDP	Gross domestic product
GWP	Global warming potential
HTP	Human toxicity potential
IM	Injection moulding
LCA	Life cycle assessment
LCC	Life cycle costing
LCEI	Life cycle environmental impact
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NC	Normalised cost
NEI	Normalised environmental impact
NPV	Net present value
OEM	Original equipment manufacturer
PA6	Polyamide 6
PET	Polyethylene terephthalate
PI	Price of impeller
PLA	Polylactic acid
$PM_{2.5}$	Fine particulate matter of 2.5 microns or less
PO	Production output
PV	Present value
$R_{E/C}$	Environment to cost relevance ratio

RPLA	Recycled polylactic acid
SDG	Sustainable development goal
SL	Service life
SLCA	Social life cycle assessment
SM	Subtractive manufacturing
TBL	Triple bottom line
TEE	Techno-eco-efficiency
UTS	Ultimate tensile stress
VPLA	Virgin polylactic acid

LIST OF PUBLICATIONS

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Journal Publications

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STATEMENT OF CONTRIBUTION OF CO-AUTHORSHIP DECLARATION

I hereby declare that I have authored and co-authored the following publications. The level of my intellectual input to each publication is indicated in the brackets below. Signed verification statements from each of my co-authors are provided in Appendices A-D.

Heshan Thenuka Wijerathne Jayawardane A/Prof Wahidul K. Biswas

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CHAPTER 1 INTRODUCTION

This thesis has been compiled as a thesis by publication. The Introduction chapter aims to provide a contextual background for the research problem that this thesis seeks to address and introduces how the succeeding chapters are linked to the articles published for achieving the research objectives of the PhD research. The following chapters thus form scholarly explanatory notes to place the thesis in the context of the established body of knowledge.

1.1 Background of the study

Manufacturing is the process of transforming raw materials into finished goods by adding value (Peng et al., 2018, Thompson, 2007). From the first industrial revolution of mechanisation of manufacturing, the manufacturing industry has undergone accelerated growth to meet the global demand for goods, culminating in the fourth industrial revolution of digital manufacturing. Manufacturing generates significant economic value, contributing 17% of the global gross domestic product (GDP) and 5.6% of Australia's GDP in 2021 (World Bank, 2021). The manufacturing industry currently employs 23% of the global workforce and 6.9% of Australia's workforce in 2021 (Australian Bureau of Statistics, 2021). However, the labour-intensive nature of the manufacturing industry has also undergone significant demographic changes due to industrial automation.

The unprecedented growth of manufacturing activity in the linear economy has resulted in high economic value but has also increased resource consumption and emissions by exceeding the world's carrying capacity (Peng et al., 2018). The manufacturing industry alone is responsible for 31% of energy usage and 27% of CO_2 emissions globally (United Nations Environment Programme, 2011). The demand for resources in the manufacturing sector, which accounts for 40% of the global material demand, has resulted in increased material extraction. The manufacturing sector accounts for 20% of total energy usage in Australia (Department of the Industry, 2020). The earth's resources are utilised faster than they can be replenished, and the atmosphere cannot absorb the emissions from manufacturing beyond its assimilative capacity, which has affected the eco-system services and human wellbeing (Keeble, 1988, Yoon et al., 2014). The excessive usage of resources, which will be exhausted in the near future, needs to be reduced through innovative manufacturing strategies.

According to Brundtland report, sustainable manufacturing should reduce the economic, environmental and social impacts of all stages of a product life cycle by utilising resources to fulfil the current manufacturing requirements without compromising future manufacturing needs (Keeble, 1988, Garetti and Taisch, 2012). Sustainable manufacturing contributes to the environmental dimension by efficiently using energy and natural resources, reducing waste, emissions, and hazardous substances, using environmentally sound materials and energy, and protecting biodiversity. In the case of economic aspects, it contributes to the economy, drives innovation, and creates job opportunities. Furthermore, it contributes to the social dimension by ensuring product safety, safe working conditions, conservation of natural resources, and maintaining good community relationships (Naghshineh et al., 2021, Huang et al., 2013).

Manufacturers are being compelled to assess the sustainability performance of their products due to strict regulations, heightened awareness among the public, and the competitive nature of the market. Sustainable manufacturing spans from short-term goals of reduction of environmental impacts of manufactured parts to long-term goals such as achieving a circular economy. It spreads across all branches of conventional and non-conventional manufacturing, including subtractive, additive, and formative methods. In this context, additive manufacturing (AM) has the potential to produce complex parts with a reduced level of resource consumption. At the same time, subtractive manufacturing has undergone a transformative change to increase resource efficiency in recent years.

Subtractive manufacturing (SM) technologies have dominated the manufacturing industry because they enable the retention of bulk material properties in manufactured parts, resulting in a significant improvement in product quality (Peng et al., 2017). However, SM has not been found to be resource efficient due to the material wastage in machining when achieving the desired shape from the work blank (Ingarao et al., 2018). The waste generated during machining, which may include lubricants, can end up in landfills and potentially lead to eco-toxicity (Fatimah et al., 2013). Furthermore, SM systems are only suitable for producing parts that can be accessed by cutting tools, which makes them unsuitable for manufacturing complex parts (Priarone and Ingarao, 2017). The use of computer numerical control (CNC) machining, which utilises 3D model data, has enhanced the energy efficiency and production of SM, while also improving product quality and minimising the need for cutting fluids (Jayal et al., 2010).

AM, on the other hand, is an emerging manufacturing process also referred to as three-dimensional (3D) printing, and is defined as “the process of adding material layer by layer from 3D model data to obtain the desired shape of the product, as opposed to subtractive manufacturing technologies” (International Organization for Standardization, 2015). AM has transformed from making prototypes, visual aids, and presentation models to a manufacturing technology for functional parts in several industrial applications (Figure 1.1) (Yoon et al., 2014, Wohler Associates, 2020). AM has the potential to emerge as a viable alternative for SM by eliminating the requirement for complicated tools, jigs, fixtures, and cutting fluids (Morrow et al., 2007). Additionally, AM offers the advantages of customisability, complex freeform fabrication, and reduced lead times (Tang et al., 2016). Finally, AM has the potential to simplify the design stage costs by enabling the production of generative designs (Thompson et al., 2019, CSIRO, 2016).

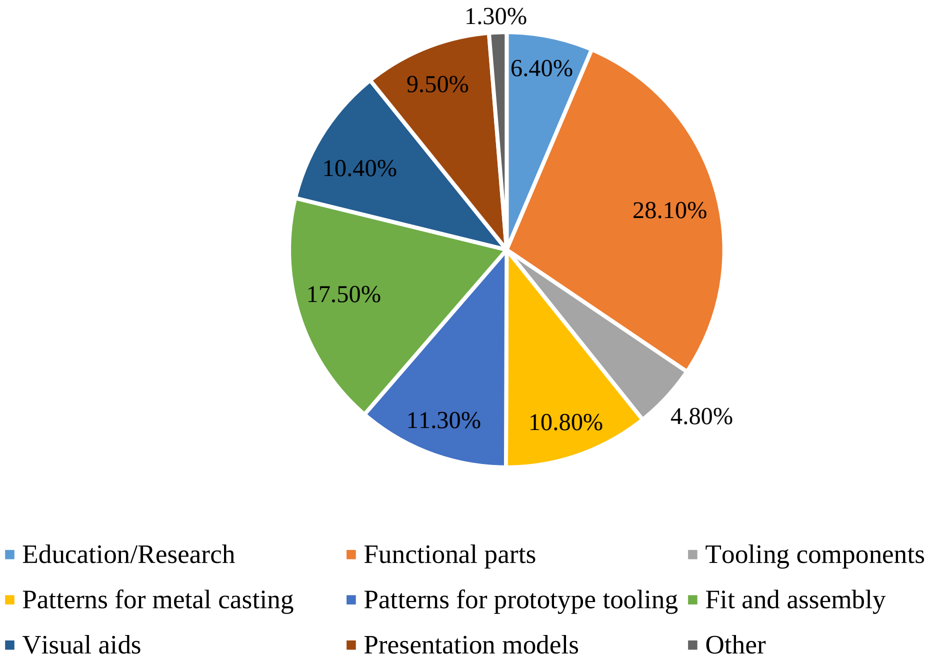


Figure 1.1: Applications of AM (Adapted from Wohler Associates (2020))

The material properties and manufacturing methods have a significant influence on the technical performance of parts (BárnikVaškoSága et al., 2019). Therefore, it is important to determine the technical feasibility of AM parts, as the additive nature of manufacturing presents inherent anisotropic material properties. Studies on the technical feasibility of AM parts remain limited due to the relatively new nature of AM technology. Furthermore, technical feasibility has not been taken into account in sustainability performance assessment studies, with the assumption that parts produced by different manufacturing methods possess identical durability and service life (Peng et al., 2017, Mami et al., 2017). However, the evaluation of technical feasibility for AM parts has been standardised by ISO 17296-3 (International Organization for Standardization, 2014). It has been measured through surface roughness, dimensional tolerance, geometrical tolerance, tensile strength, hardness, impact strength, fatigue strength, density, porosity, and microstructure, depending on the application. Additionally, it is crucial to evaluate the performance of AM parts during the usage stage to determine whether AM has any impact on the product's durability and service life, as it could have implications for the environmental and economic feasibility of the manufactured parts.

Several studies have shown that the environmental life cycle assessment (ELCA) is an effective tool for evaluating the environmental impact of manufactured parts (Peng et al., 2020, Ma et al., 2018, Paris et al., 2016). In the ELCA, the goal and scope of the study are first established, then the inventory consisting of inputs and outputs during the life cycle is compiled, then the life cycle environmental impacts (LCEI) are ascertained through a product life cycle assessment, and finally, LCEI results are interpreted for cause diagnosis and the determination of improvement strategies (Serres et al., 2011).

The economic impacts of manufacturing systems have been predominantly studied using a life cycle costing (LCC) approach where the cost associated with manufacturer and user from the cradle to grave are evaluated using the same life cycle inventory (LCI) that was used for the ELCA analysis (Atzeni and Salmi, 2012, Gebler et al., 2014). Developments in additive manufacturing technology have offered economic benefits such as production flexibility, reduced machine costs, reduced material costs, reduced material, and reduced energy wastage. Using LCC, the capital investment costs of additive manufacturing have been found to be offset by cheaper operating costs (Pereira et al., 2018).

It is essential to explore the environmental impact reduction of manufactured parts per dollar invested when implementing environmental improvement strategies in manufacturing, as this can help to balance economic and environmental considerations (Mami et al., 2017). The eco-efficiency analysis is a valuable framework for evaluating the economic and environmental sustainability of technically feasible parts. By considering economic and environmental impacts together, this analysis enables the identification of cost-competitive and environmentally friendly options (Kicherer et al., 2006). Furthermore, eco-efficiency analysis could be linked with hotspot identification to implement eco-efficiency improvement strategies such as the use of recycled material feedstock. Recycled materials lower the environmental impacts and costs associated with the material processing stage by diverting plastic waste to the manufacturing of functional material (Cruz Sanchez et al., 2020).

Switching from conventional processes to additive manufacturing processes could result in numerous social impacts, such as development of new skills, level of employment, health and safety, and resource conservation (Huang et al., 2013, Ma et al., 2018). It is important to conduct a comprehensive assessment of AM that considers not only its technical, economic, and environmental impacts but also its social impacts, which depicts the overall sustainability of AM as a manufacturing technology.

This thesis has examined the techno-eco-efficiency performance of parts produced through AM and has compared it with parts produced through SM. The study aims to evaluate the technical, economic, and environmental effectiveness of AM parts while also assessing the social implications of developing technically feasible and eco-efficient parts.

1.2 Problem statement

The research study has identified the following research questions to investigate the sustainability performance of additive and subtractive manufactured parts.

1. How is the technical feasibility of additive manufactured parts determined?
2. How can technical feasibility be integrated into sustainability assessment?
3. What are the drawbacks of existing sustainability performance assessments?
4. How can a sustainability assessment framework be developed to overcome existing weaknesses for selecting sustainable option(s)?
5. What are the hotspots or problematic areas responsible for poor sustainability performance?
6. What strategies could improve the sustainability performance of parts?

1.3 Aim, objectives, and scope

This research aims to develop a 'techno-eco-efficiency' framework to assess the technical, economic, and environmental performance of AM parts in comparison with SM parts as a decision support tool. Moreover, the research aims to assess the eco-efficiency improvement strategy of material recycling and social impacts of techno-eco-efficient options. In order to achieve this aim, the following research objectives have been formulated.

Research objective 1: Article 1 – Literature Review (Appendix A – Article 1)

- *To review the state of the art of technical feasibility studies and sustainability assessment methods for assessing additive and subtractive manufactured parts, and to identify the research gaps that can be overcome through this PhD research.*

A comprehensive literature review has been conducted on the state of the art in technical feasibility and sustainability assessment methods for assessing additive and subtractive manufactured parts. The review identified the need to assess technical feasibility prior to sustainability assessment and the need for a holistic and comprehensive framework that combined technical feasibility, environmental impacts, and life cycle costs.

The refereed articles so far reviewed were found to assess the technical feasibility of additive manufactured parts by determining limited technical parameters. Further, environmental life cycle assessment (ELCA), life cycle costing (LCC), and social life cycle assessment (SLCA) tools have been applied to determine triple bottom line (TBL) indicators of environmental, economic, and social impacts. However, the review has found the absence of the integration of these tools for TBL sustainability assessment and the absence of technical assessment in the sustainability assessment of manufacturing strategies. Eco-efficiency assessment framework that combines environmental impacts with life cycle costs, was found to assess the eco-efficiency of products in most of the sectors except for manufacturing. The current research integrated the eco-efficiency framework with technical and social impact assessments to compare the sustainability performance of AM parts with SM parts.

Research objective 2: Articles 2 (Appendix B) and 3 (Appendix C)

- *To assess the technical properties and performance of additive and subtractive manufactured parts.*

As the literature review identified the need for technical feasibility prior to sustainability assessment, the next research objective was formulated to investigate the technical feasibility of manufactured parts. The layer-by-layer addition of material in AM significantly affects the microstructure of the AM parts, which tends to exhibit anisotropic material properties. In the case of SM, machining minimally affects the material properties. Therefore, the technical performance of parts manufactured through different manufacturing methods needs to be assessed by measuring mechanical properties, including surface roughness, dimensional tolerance, geometric tolerance, tensile strength, fatigue strength, microstructure, porosity, and density and by assessing the technical performance in a functional application using standard testing methods.

Research objective 3: Articles 2 (Appendix B) and 3 (Appendix C)

- *To assess the environmental impacts and life cycle costs using ELCA and LCC tools.*

Once additive and subtractive manufactured parts have been found technically feasible, the sustainability performance should be assessed. The literature review found that economic and environmental impacts of the manufactured parts are significant aspects of the triple bottom line of sustainability, which need to be assessed using ELCA and LCC methods. According to ISO 14040-44, the ELCA includes goal and scope identification, calculation of inputs and outputs of the product system to formulate the life cycle inventory, calculation of the life cycle impacts, and interpretation results for environmental hotspot identification and cause diagnosis. The functional unit of the ELCA is based on the '*delivery of fluid by a part during the service life'* derived from the technical assessment (i.e., fatigue test) of the manufactured parts. A mass balance was conducted on the basis of this functional unit for developing an LCI. Once the LCI has been developed, the inputs and outputs were converted to environmental impact indicators. The indicators were selected through an expert survey involving academia, industry, and the government of Australia. The life cycle costing (LCC) method was used to calculate the economic impacts of manufactured parts using the same goal, scope, and life cycle inventory considered for the ELCA analysis.

***Research objective 4**: Articles 2 (Appendix B) and 3 (Appendix C)*

- *To integrate the technical, environmental, and economic aspects of manufactured parts into the 'techno-eco-efficiency' framework*

As the literature review identified the need for an integrated approach to assess the sustainability performance, the 'techno-eco-efficiency' framework was developed. The aim of the techno-eco-efficiency (TEE) framework is to use the results of technical feasibility, ELCA, and LCC to determine the techno-eco-efficiency performance of manufactured parts. The technical performance has been integrated into the eco-efficiency assessment by using the functional unit. The eco-efficiency portfolios of the manufactured products, which were determined by using the TEE framework, determine if the product is eco-efficient or not. The portfolio analysis has been used to select the most techno-eco-efficient option, which is technically, economically, and environmentally viable. Furthermore, the environmental and economic hotspots of eco-efficient and eco-inefficient options have been identified through the hotspot analysis.

Research objective 5: Article 4 (Appendix D)

- *To manufacture parts from recycled materials and assess the techno-eco-efficiency performance*

The incorporation of this research objective enabled the conversion of the original MPhil programme to the PhD programme. The hotspot analysis using an ELCA approach revealed that the material processing stage of virgin polymer composites contributes most to the life cycle environmental impact of additive manufactured parts. Accordingly, the eco-efficiency improvement strategy of material recycling and the use of recycled materials as feedstock for AM has been considered and then assessed by utilising the techno-eco-efficiency framework. The study has used pre-consumer polylactic acid (PLA) waste from AM, which has been mechanically recycled into AM feedstock filament. The techno-eco-efficiency framework assessed whether the AM parts made of pre-consumer PLA waste are technically, environmentally, and economically feasible.

Research objective 6: Article 4 (Appendix D)

- *To assess the social impacts of techno-eco-efficient options*

This research objective has also been incorporated during the PhD conversion. The adoption of AM in place of conventional manufacturing processes may have substantial social implications. Even though there are significant social impacts in manufacturing, the assessment of such impacts remains highly restricted owing to challenges associated with measuring relevant indicators. The study has assessed the social impacts of ‘techno-eco-efficient’ options, considering the stakeholders, including employees, local community, and society in the social life cycle assessment (SLCA) for determining the social implications of the techno-eco-efficient products.

1.4 Research Methods

The technical feasibility assessment was conducted for all the manufactured parts to measure the technical properties of surface roughness, dimensional tolerance, geometric tolerance, tensile strength, fatigue strength, microstructure, porosity, density, and technical performance in a functional application. Tests were carried out with standard test specimens and manufactured parts following standard testing methods. The parts meeting the technical benchmark for all assessments were deemed technically feasible.

The environmental life cycle assessment was conducted according to the ISO 14040-44 standard. The system boundary includes all the life cycle stages from the design stage to use stage, with each technically feasible impeller being evaluated for its service life during the use stage. An LCI was developed by examining the inputs and outputs of different life cycle stages, such as energy, material, labour, emissions, and waste. The study used the input from an expert survey to select environmental impact indicators relevant to the manufacturing industry in Australia. The SimaPro software was used to calculate the environmental impacts of each impeller. The results of the impact assessment were interpreted using network diagrams for environmental hotspot analysis.

Life cycle cost analysis was done for the same goal and scope considered in ELCA, following AS/NZS 4536:1999 (Standards Australia/ Standards New Zealand, 1999). The LCC was calculated in two stages (i.e., production of impellers and pumping using impellers over their service life) using Microsoft Excel software.

The results of the ELCA and LCC were incorporated into the TEE framework to determine the eco-efficiency portfolio positions of the manufactured parts using the following steps. Firstly, normalised costs (NC) were obtained by dividing with the gross domestic product per inhabitant (GDP/Inh), and normalised environmental impacts (NEI) were obtained with gross domestic environmental impact per inhabitant (GDEI/Inh), respectively. The NEIs were then multiplied by the corresponding weights obtained from the expert survey to obtain the relative importance of each category in the Australian manufacturing industry. The NC and NEI were used to determine the eco-efficiency portfolio positions (Kicherer et al., 2006, Saling et al., 2002).

In this study, the social impacts of AM parts were evaluated through the Social Life Cycle Assessment (SLCA) framework, which utilised the same goal, scope, and LCI as the ELCA and LCC methods. The SLCA was conducted with a stakeholder-driven framework, which included employees, local community, and society. Social impacts were calculated from data from LCI. The social impacts on employees were examined through health and safety and level of employment, while the social impacts on the local community and society were assessed through the conservation of natural resources and reduction of landfilling implications.

1.5 Significance

The purpose of the study is to develop a comprehensive framework to evaluate and compare the 'techno-eco-efficiency' performance of additive and subtractive manufactured parts. This research contributes valuable insights into the manufacturing industry by offering a decision-support tool for selecting sustainable manufacturing methods. Furthermore, the proposed framework could also be used as a tool to identify economic and environmental hotspots in the existing manufacturing technologies to implement eco-efficiency improvement strategies such as material recycling. Moreover, the study investigates the social impacts of AM and material recycling in a life cycle approach, which could be used to address social impacts pertinent to manufacturing. Ultimately, this research seeks to contribute to the ongoing discourse on sustainable manufacturing practices by providing a more holistic evaluation of digital manufacturing technologies.

1.6 Limitations

The applications of the TEE framework in this study were limited to the nylon-carbon fibre composite in terms of virgin polymer composite and stainless steel 316L in terms of metals. In the eco-efficiency improvement scenario, the mechanical recycling of virgin nylon-carbon fibre composite was found to be difficult due to heterogeneity of the composition and degradation of properties. Further, the hygroscopic nature of the nylon material was observed during material recycling processing, resulting in lower material properties and polymer degradation. Therefore, recycled PLA material was selected as a feasible material for material recycling, which has technical properties similar to nylon (PA6). The SLCA in this study used a quantitative approach to assess the social impacts of additive manufactured parts and recycled materials, which was limited to the stakeholders of employees, local community, and society.

1.7 Thesis Structure

The thesis has been compiled as a thesis by publication. The structure of the thesis has been presented in Figure 1.2, which provides an overview of the organisation of the study. The six chapters of this thesis have been designed to provide a comprehensive evaluation of the sustainability performance of AM parts in comparison with SM parts using the ‘techno-eco-efficiency’ framework. Each chapter consist of scholarly explanatory notes for publications, which contribute to achieving the overall research objectives, address the identified research gaps, and synthesise the study.

Chapter 1: This chapter serves as an introduction to the study, providing an overview of the background, objectives, research methods, significance, and limitations of the research. This chapter sets the context for the research and outlines the motivation for the study.

Chapter 2: This chapter presents the literature review, which critically evaluates the existing research on additive manufacturing, subtractive manufacturing, technical feasibility assessment, life cycle assessment (LCA), other environmental impact assessment methods, life cycle costing (LCC), and eco-efficiency assessment (EEA). The explanatory note on literature review aims to identify the gaps in existing knowledge and provides a foundation for the development of the ‘techno-eco-efficiency’ framework.

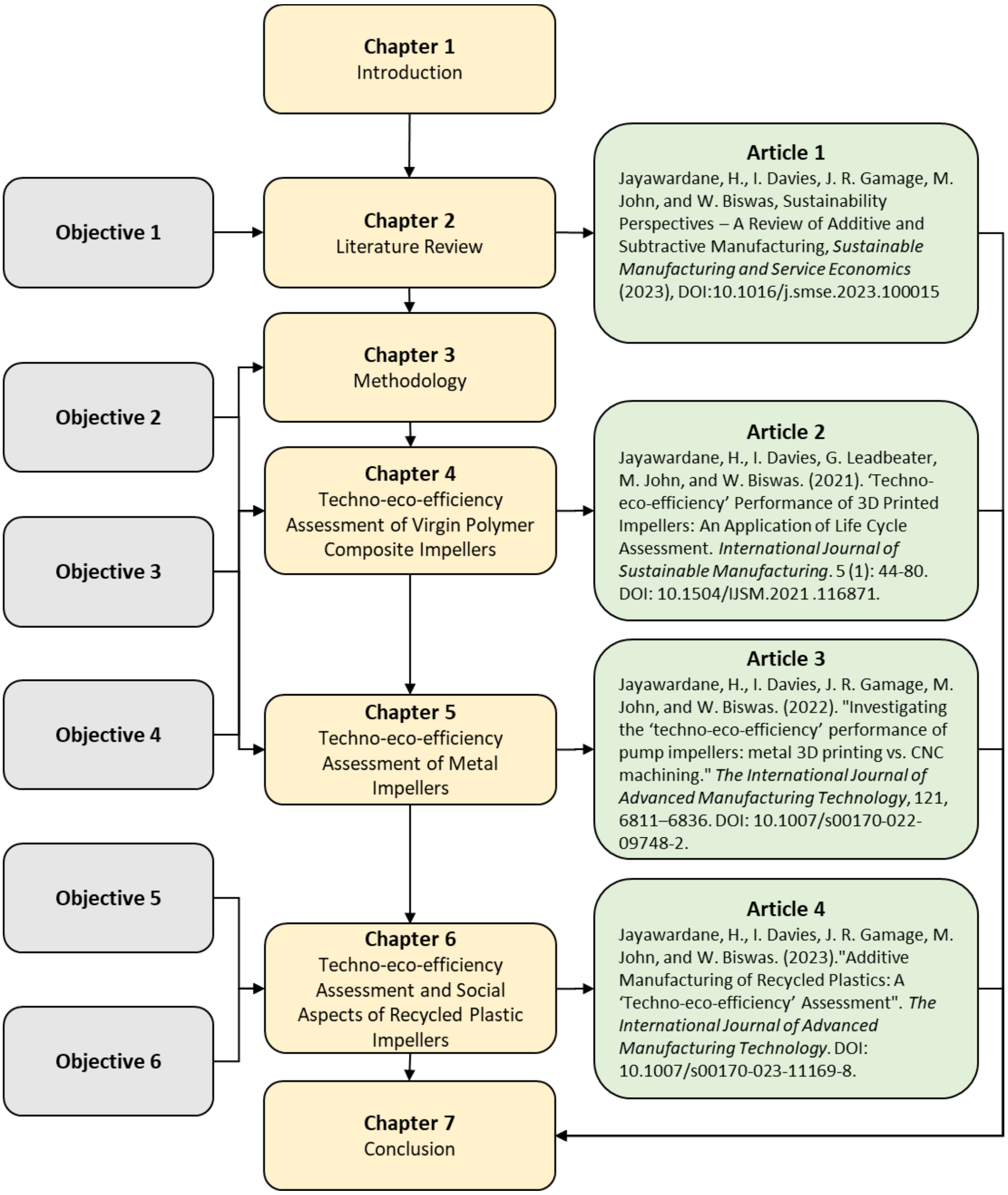
Chapter 3: This chapter outlines the research methodology of the study, which includes the development of the innovative ‘techno-eco-efficiency’ framework, which is the theoretical framework of the study. The development of the framework was published in the Article 2.

Chapter 4: The chapter presents the techno-eco-efficiency performance assessment of virgin polymer composite parts made through additive and subtractive manufacturing.

Chapter 5: This chapter presents the validation of the ‘techno-eco-efficiency’ framework in the context of metallic materials, which was published in Article 3. The parts made from a novel metal additive manufacturing technology were compared with subtractive manufactured parts.

Chapter 6: This chapter explores techno-eco-efficiency improvement strategies such as the use of recycled materials as feedstock for additive manufacturing and evaluates the techno-eco-efficiency performance of recycled AM parts in comparison with virgin AM parts, SM parts, and injection moulded parts. Additionally, the chapter examines the social impacts of additive manufactured parts and recycled materials. This work has been published in the final Article.

Chapter 7: This chapter summarises the main findings of the study and explains how the research objectives have been achieved through the published articles. The chapter further presents the recommendations and future work of the research study, highlighting areas for potential improvements to the developed techno-eco-efficiency framework.



Article 1

Jayawardane, H., I. Davies, J. R. Gamage, M. John, and W. Biswas, Sustainability Perspectives – A Review of Additive and Subtractive Manufacturing, *Sustainable Manufacturing and Service Economics* (2023), DOI:10.1016/j.smse.2023.100015

Article 2

Jayawardane, H., I. Davies, G. Leadbeater, M. John, and W. Biswas. (2021). 'Techno-eco-efficiency' Performance of 3D Printed Impellers: An Application of Life Cycle Assessment. *International Journal of Sustainable Manufacturing*. 5 (1): 44-80. DOI: 10.1504/IJSM.2021 .116871.

Article 3

Jayawardane, H., I. Davies, J. R. Gamage, M. John, and W. Biswas. (2022). "Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining." *The International Journal of Advanced Manufacturing Technology*, 121, 6811–6836. DOI: 10.1007/s00170-022-09748-2.

Article 4

Jayawardane, H., I. Davies, J. R. Gamage, M. John, and W. Biswas. (2023)."Additive Manufacturing of Recycled Plastics: A 'Techno-eco-efficiency' Assessment". *The International Journal of Advanced Manufacturing Technology*. DOI: 10.1007/s00170-023-11169-8.

Figure 1.2: Thesis structure

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CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The objective of this chapter is to review the state of the art of technical feasibility and sustainability assessment methods for assessing additive and subtractive manufactured parts, and to identify the research gaps that can be overcome in this study.

The findings of the literature review have been published as ‘Sustainability Perspectives – A Review of Additive and Subtractive Manufacturing’ in the Journal of Sustainable Manufacturing and Service Economics, which has been included in **Article 1 – Appendix A.**

The article employs a systematic literature review (SLR) methodology. The keywords and scope were defined from the aim of the research. The following keywords were used in a structured search term (“sustainable manufacturing” OR “3D printing” OR “additive manufacturing” OR “machining” OR “subtractive manufacturing”) AND (“technical feasibility” OR “life cycle assessment” OR “life cycle costing” OR “social life cycle assessment”) for the literature review. The article search received 2,110 articles and 92 articles were selected for the review through a rigorous article screening process. Articles were reviewed focusing on manufacturing processes, technical feasibility assessment, triple bottom line sustainability assessment tools, and sustainability comparison methods.

2.2 Manufacturing Processes

The literature on process selection, part selection, and material selection has been reviewed to become conversant with the established body of knowledge in the context of manufacturing processes,. Several studies have assessed the capability of additive manufacturing (AM) process alongside subtractive manufacturing (SM) since they are two approaches of manufacturing (Watson and Taminger, 2018, Acerbi and Taisch, 2020). AM was found to eliminate the need for complex tools, fixtures, and jigs, enabling just-in-time (JIT) manufacturing (Tang et al., 2016). However, the process did not offer significant economy of scale compared to subtractive manufacturing and injection moulding (Huang et al., 2016).

Further, the studies have found that the design parameters such as complexity (Peng et al., 2020), solid-envelope ratio (Watson and Taminger, 2018), application (Huang et al., 2016), and functionality (Yoon et al., 2014) have influenced the selection of AM over SM to manufacture parts. Moreover, AM technology has faced challenges with the product quality due to the anisotropic material composition of AM materials compared to the isotropic composition of Subtractive Manufacturing (SM) materials (Ford and Despeisse, 2016). Additionally, the high cost of materials, limitations on the range of materials available for production, and limited recyclability of materials and parts have also hindered the adoption of AM technology.

2.3 Technical feasibility assessment

The technical properties of parts have not been significantly considered when AM technology was only used for prototypes (Kim et al., 2017). However, in the applications of AM to produce safety-critical parts, such as aeronautical, medical, and industrial appliances, technical feasibility has been considered (BárnikVaškoHandrik et al., 2019, Khalid and Peng, 2021). Studies have assessed the technical feasibility of AM and SM parts through mechanical characterisation tests, build material property assessments, and performance tests. The microstructure examination of the fracture surface of test specimens has been used in several studies to examine the variation of technical performance of parts made through AM. This has been found to effectively identify defects resulting in poor technical performance (Jiang and Ning, 2021).

However, due to the variety of process parameters, post-processing, and materials used in AM, it has been difficult to validate, regulate, and certify the technical feasibility of AM parts (Yoon et al., 2014). The technical aspects (reliability, durability, and service life) of AM parts have been widely disregarded in sustainability assessments, thereby implicitly assuming similar technical performance to conventional SM counterparts (Ma et al., 2018). The literature reviewed in this study showed that the technical feasibility assessment of AM parts is imperative for comparative sustainability assessment with SM parts (Huang et al., 2016, Serres et al., 2011).

2.4 Triple Bottom Line (TBL) sustainability assessment methods

The reviewed studies have individually assessed the triple bottom line objectives of environmental, economic, and social impacts (Saade et al., 2020). However, the integration of these impacts has not been adequately applied or researched.

2.4.1 Environmental impacts

The growing significance of environmental impacts in sustainability assessments has stimulated the research interest in assessing the environmental impacts of AM and SM parts. Several frameworks, such as energy consumption modelling (Peng et al., 2018, Dudek and Zagórski, 2017) and environmental life cycle assessment (ELCA) with different indicators and indicator types have been used for this purpose (Saade et al., 2020). The life cycle approach using ELCA has been the most widely used in several studies (Mami et al., 2017, Ma et al., 2018, Peng et al., 2020). The sustainability potential of AM has been evaluated through parameters such as scale of production, technology adoption scenarios, and use of recycled feedstock. However, studies have reported limited availability of information regarding life cycle inputs and outputs in terms of energy consumption, material consumption, and process emissions, which have hindered the accuracy of the ELCA.

Several environmental hotspots of AM have been identified, which include part weight, lower build volume utilisation, lower machine utilisation, material waste, energy mix, and high energy consumption. The resource consumption in feedstock and waste associated with the disposal of end-of-life products has a significant bearing on the triple bottom line objectives of the sustainability performance of manufactured parts. A few studies have investigated the sustainability performance of AM parts made of recycled materials. However, there is limited research on the technical investigation of parts made from recycled feedstock using different technologies, leaving much of this research area unexplored.

2.4.2 Economic impacts

The reviewed studies have highlighted the significance of cost as an important consideration in business decision-making. The studies have used widely used life cycle costing (LCC) to determine economic impacts of manufactured parts. The findings suggest that the life cycle costs of AM parts are higher than their SM counterparts, mainly due to high capital costs. However, further technological developments and the expiration of intellectual property rights of AM processes are expected to reduce capital costs of AM in future. Some studies have also considered life cycle costs along with environmental impacts for comprehensive analysis of triple bottom line objectives. There is a need for the integration of LCC with ELCA to improve decision making process for selecting the cost-competitive and environmentally friendly option(s).

2.4.3 Social impacts

Studies on social impact assessment of additive and subtractive manufacturing are limited due to the qualitative nature of some social impact indicators. However, the social life cycle assessment (SLCA) framework has gained interest among researchers as a framework to conduct comprehensive social impact assessments (Naghshineh et al., 2021). Similar to other LCA frameworks, SLCA could be used to attain the same goal, scope, and LCI to provide a comprehensive assessment of the social impacts of manufactured parts (Ma et al., 2018).

AM methods have been found to have positive social impacts, such as reduced occupational hazards and increased job satisfaction, but it has also contributed to several negative impacts such as job losses and higher amounts of human toxicity potential (Matos et al., 2019). There could be other social impacts indicators suitable for assessing manufactured parts, which should be carefully selected through consultation of reports and relevant stakeholders.

2.5 Integration and Comparison

Comparative assessment of manufacturing technologies to determine the feasibility of manufacturing a part is an important aspect of decision making in modern manufacturing (Attaran, 2017). A fair and effective comparison should include all aspects of triple bottom line in the sustainable manufacturing system (Fatimah et al., 2013). Several studies have developed decision support comparison tools based on resource consumption (Watson and Taminger, 2018), technical feasibility (Bikas et al., 2019), batch size (Ingarao et al., 2016), and solid to cavity ratio (Ingarao et al., 2018). However, these approaches have failed to capture the holistic overview of multiple parameters.

Eco-efficiency analysis has received recent attention from several studies, given the potential to integrate environmental implications from ELCA and economic implications from LCC into a single indicator (Ma et al., 2018). In addition, the ability to incorporate improvement strategies and the use of 'distance to target' approaches have made it suitable for comparative assessment. However, there are challenges associated with the integration of technical feasibility aspects into the sustainability performance assessment frameworks for manufacturing (Gebler et al., 2014). Most sustainability assessment tools and methods assume AM parts have similar technical feasibility as SM parts which does not accurately assess the implications of the technical performance on the sustainability assessment (Mami et al., 2017).

2.6 Research gaps

Although general solutions have been proposed in several studies, specific research gaps remain unexplored in the context of sustainability performance comparison of AM and SM parts. The following research gaps were identified from the literature review.

- The applicability of AM process to manufacture functional parts needs to be explored through technical feasibility assessment.
- The technical feasibility assessment of manufactured parts needs to be integrated into sustainability assessment methods.
- The sustainability assessment methods need to be integrated, which could also allow comparison and improvement of options. Thus, there is an urgent need to develop a holistic framework that could integrate technical, environmental, and economic aspects of AM and SM parts.
- The social aspects of AM and SM parts have received limited consideration. Social impacts or implications of technically feasible, cost-competitive, and environmentally benign options need to be further explored.
- There is a need to explore environmental improvement opportunities of the material processing of AM by using recycled feedstock.

The comprehensive literature review presented in **Article 1 – Appendix A**, grounds the work in this research study in the established body of knowledge. The scholarly explanatory note presented in the chapter is a summary of the published article on the literature review of this PhD work and is not exhaustive. Therefore, the published literature review should be referred for an effective insight to the research gaps this thesis seeks to address.

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CHAPTER 3 METHODOLOGY

3.1 Introduction

The aim of this chapter is to develop a comprehensive framework to assess the technical, environmental, and economic impacts of manufacturing strategies. The methodology consists of two phases.

In the first phase, a TEE framework was developed to assess the eco-efficiency performance of technically feasible parts. According to the framework, the first task was to assess the technical performance of AM parts made from virgin polymer composites and metals, followed by economic and environmental assessment of only the technically feasible parts. The methodology was published in two articles, entitled ‘techno-eco-efficiency assessment of additive and subtractive manufactured parts: an application of life cycle assessment’ in the International Journal of Sustainable Manufacturing (**Article 2 – Appendix B**), and ‘Investigating the ‘techno-eco-efficiency’ performance of pump impellers: metal 3D printing vs. CNC machining.’ in the International Journal of Advanced Manufacturing Technology (**Article 3 – Appendix C)**.

In the second phase, the social impact analysis was added to the TEE framework for assessing the EE of AM virgin polymer composites and metallic parts and assessing the environmental, economic, and social impacts of recycled PLA parts. This updated methodology was published in the article entitled ‘Additive manufacturing recycled plastics: A techno-eco-efficiency assessment’, published in the International Journal of Advanced Manufacturing Technology (**Appendix 1 – Article 4)**.

3.2 Techno-eco-efficiency framework

The ‘techno-eco-efficiency’ (TEE) framework addresses the research gaps identified from the literature review (Figure 3.1). The purpose of implementing this framework was to facilitate informed decision-making for the manufacturing industry in the selection of AM parts that have the potential to meet functional requirements in an economically and environmentally sustainable manner.

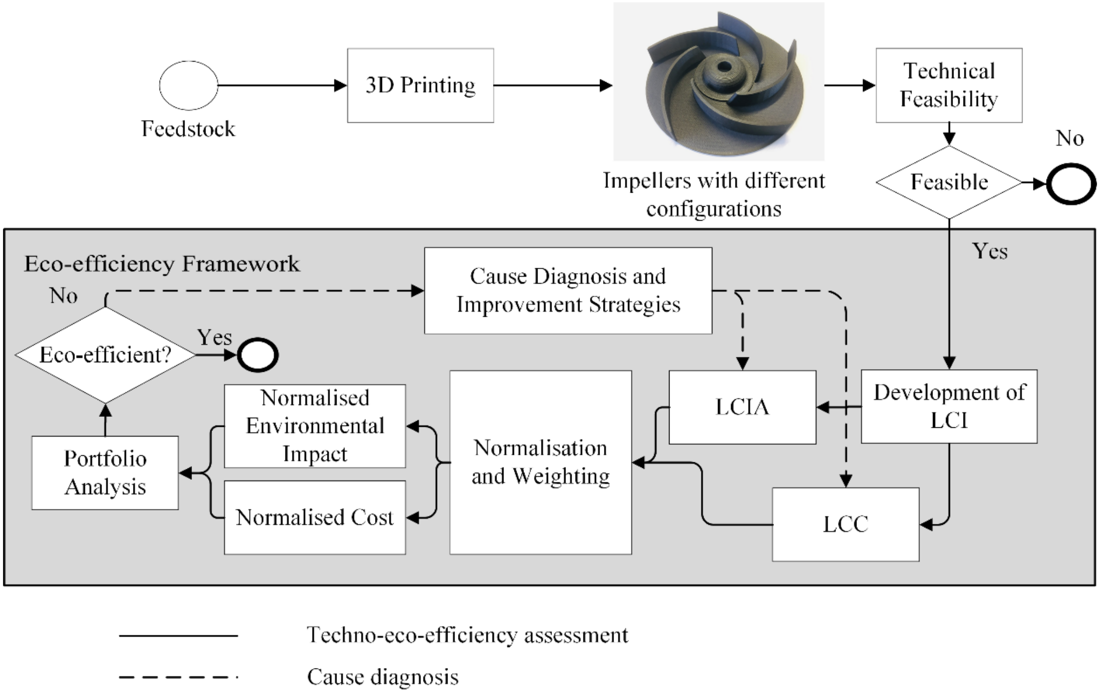

Figure 3.1: Techno-eco-efficiency framework (**Article 2 – Appendix B**)

The framework consists of the following steps. The first step is the selection of parts, materials, and processes which are suitable for the assessment and feasible for the application. The second step is to assess the technical feasibility of parts through assessment of technical properties and performance in a functional application. Only the technically feasible parts are selected for further assessment in the framework. The next step is to discern eco-efficient options by combining ELCA and LCC through the eco-efficiency portfolio analysis. If some options are found to be not eco-efficient, causes are diagnosed by hotspot analysis using an LCA approach and relevant improvement strategies are implemented to treat the environmental and economic hotspots. The TEE framework enables iterative and comparative assessment of options.

Step 1: Parts, materials, processes selection

In the first step of the TEE framework, appropriate materials and parts were selected for additive manufacturing. A product portfolio consisting of four items, including spur gear, turbine impeller, semi-open pump impeller, and closed pump impeller, was evaluated based on a multi-criteria decision-making model (Section 2.2.1 of **article 2 – Appendix B**). The semi-open centrifugal pump impeller from a wastewater pump received the highest feasibility score. The hydraulic performance testing method was also considered to evaluate the overall feasibility of the product for the intended use.

Table 3.1 presents how the materials and processes were selected for AM. Materials for AM were selected based on similarity to OEM material, mechanical properties, and availability.

The processes for AM were selected based on the feasibility and availability. Similar materials and processes were selected for the SM benchmark.

Table 3.1: Materials and processes selection for AM

Material	Process
Virgin polymer (carbon fibre-nylon)	Fused filament fabrication by Markforged Mark 2.
Metal (Stainless steel 316L)	Bound metal extrusion by Desktop Metal Studio

Step 2: Technical feasibility assessment

The technical feasibility of AM parts with different configurations was assessed by comparing their technical properties with the parts manufactured by conventional SM process. The technical properties of tensile properties, fatigue properties, surface roughness, microstructure, dimensional tolerance, and product density were tested as outlined in ISO 17296-3 for Additive Manufacturing (International Organization for Standardization, 2014). Further, a mutual acceptance test was also conducted to compare the functional performance of the AM parts with the SM and OEM benchmarks.

Tensile properties – the tensile properties of the impeller were evaluated by performing a tensile test using a universal testing machine. The ASTM D638 standard was used to test polymer composites, while the ASTM E8M standard was used to test metals. The yield strength, ultimate tensile strength (UTS), and Young's modulus were calculated to assess the impeller's durability and service life.

Fatigue properties – the fatigue life is an important factor in determining the durability and service life of a pump impeller, which is crucial for sustainability. A low cycle fatigue test was conducted, adhering to the ASTM D7791-17 standard with a universal testing machine for polymer composites, and the ISO 22407:2021 standard with a rotating bending fatigue testing machine for metals. For each configuration, nine test samples were subjected to stress levels of 90%, 85%, and 80% of the UTS. A test frequency of 1 Hz and a stress ratio (R) of 0.1 were used for each test. The outcome of the tests was used to construct the S-N curves for the materials, utilising the Basquin’s equation (Eq.(1)), which is applicable for the limited region of the impellers' fatigue life. The equation considers the tensile stress (S), the number of cycles until failure (N), and material constants (A and B) (Pertuz et al., 2020). The fatigue strength of the SM material was considered for comparison. The fatigue life of the impellers was determined by multiplying the number of cycles to failure with the pump speed, as expressed by the Eq.(2).

$$S = A \times N^{B} \tag{1}$$

$$Estimated\ fatigue\ life\ (h) = N/Pump\ speed(cycles/h) \tag{2}$$

Surface properties – surface roughness was measured using a *Mitutoyo SJ-201* profilometer to determine its impact on hydraulic and frictional losses in the pump impeller. The mean surface roughness (Ra) of the shrouds and vanes was compared with the surface roughness of the SM part used as a benchmark for comparison.

Fracture surface examination – the examination of fracture surface of test specimens could be used to identify the presence of defects and porosity, which could affect the mechanical properties materials (Pertuz et al., 2020). The fracture surfaces of the specimens were examined to investigate the macrostructure, but no direct comparisons were made due to the absence of quantified defects and voids.

Geometric properties –the geometric properties of the impeller, such as the tolerances of the outer diameter, inner diameter, and vane and shroud thickness, were carefully measured in order to assess their accuracy and ensure that they met the required specifications. To provide a basis for comparison, the tolerances of the SM part were used as a benchmark against which the measurements of the impeller were evaluated. This allowed for a thorough analysis of the impeller's geometric properties and ensured that it was manufactured to the necessary standards.

Product density – The presence of defects and voids in AM parts makes product density a crucial property (Terekhina et al., 2019). The density of the AM part was measured and compared to that of the SM part, following the AS 1141.5 – 2000 standard.

Hydraulic performance test – the hydraulic performance of each pump impeller was measured using a pump test rig (Figure 3.2) in compliance with the ISO 9906 standard (International Organization for Standardization, 2012). The static suction head (H_s) was calculated (Eq.(3)) by the water level at the suction point (h), while the discharge head (H_d) was measured by a pressure gauge at the discharge point. The pump head ($H_{pump,\ n}$) was calculated assuming no pressure loss, with the Eq.(4), which included impeller type (n), the density of water ($\rho_{w)}$, and acceleration due to gravity (g). The flow rate ($\dot{Q}$) was measured using a flowmeter and a stopwatch.

$$H_s = h \times \rho_w \times g \tag{3}$$

$$H_{pump,n} = H_{d,n} - H_s \tag{4}$$

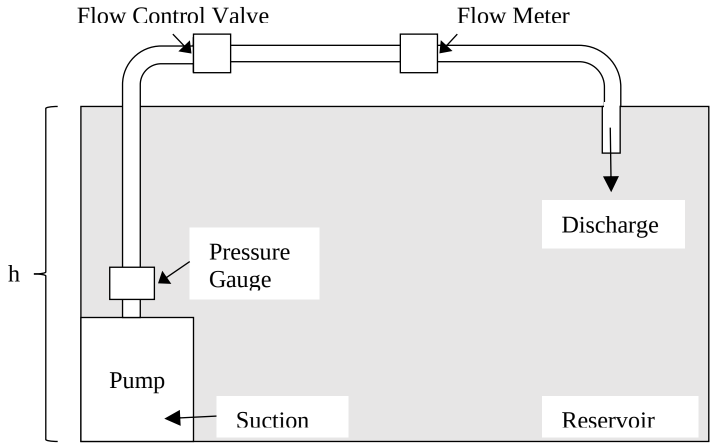

Figure 3.2: Hydraulic performance test rig (**Article 2 – Appendix B**)

Finally, the determination of energy consumption for each impeller necessitated the computation of head (H) vs. flow rate ($\dot{Q}$) curves, commonly referred to as pump performance curves. The resulting pump performance curves for the AM parts were compared to those of the SM parts and the pump impeller from the original equipment manufacturer (OEM).

Step 3: Eco-efficiency (EE) assessment

After careful consideration, only technically feasible options were selected for the eco-efficiency (EE) assessment. The technical feasibility of pump impellers was integrated into the EE assessment using the estimated service life of the manufactured parts, which was used as the functional unit of ELCA and LCC tools. The service life of the impeller was calculated from the lower value of estimated fatigue life and the market data on service life, accounting for wear and corrosion.

The AM parts were assessed by the ELCA and LCC tools to determine the environmental impacts and life cycle costs of the AM parts in comparison with SM parts, for the EE analysis (Kicherer et al., 2006).

Environmental life cycle assessment (ELCA) – an ELCA was conducted on the technically feasible impellers in accordance with the ISO 14040/44 standard (International Organisation for Standardization, 2006). The most important part of the goal definition in a comparative ELCA is the identification of functional unit (Hauschild et al., 2018). The obligatory property of fluid delivery was used as the function of the pump impeller. The functional unit was defined as '*the delivery of fluid during the service life of the impeller*'. The scope of the ELCA included all the life cycle stages from 'design to use', as shown in Figure 3.3. The methodology has been included in Section 2.3 in **article 2 – Appendix B**.

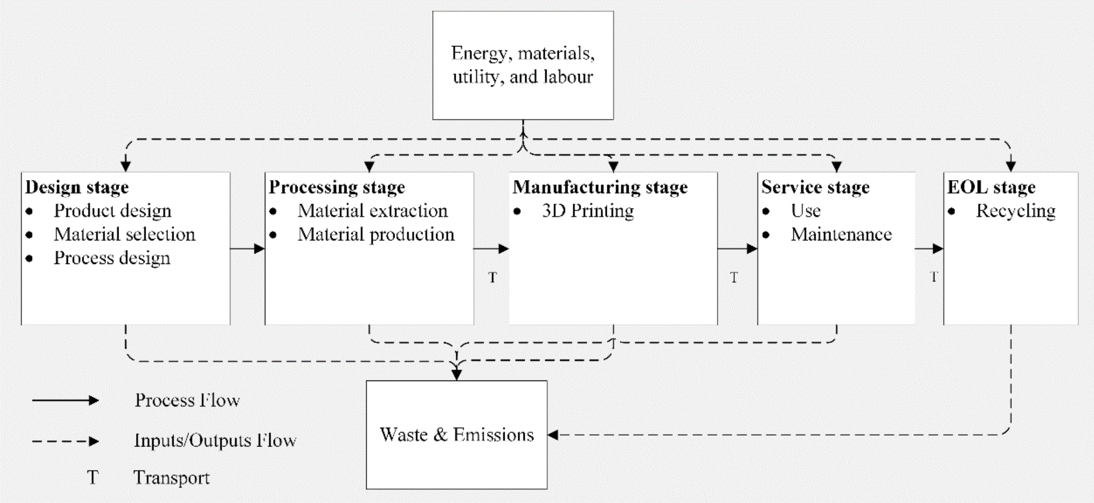

Figure 3.3: The scope of ELCA (**Article 2 – Appendix B**)

The inputs and outputs of energy, materials, utility, labour, waste, and emissions associated with all the life cycle stages were used to develop the life cycle inventory (LCI). The environmental impacts were calculated by incorporating LCI into *SimaPro* LCA software (Arceo et al., 2019).

- Development of environmental impact indicators

In order to select environmental impact indicators that are relevant to the manufacturing industry in Australia, an expert survey was conducted across thirty stakeholders in Academia, Industry, and Government. The ranks assigned by the respondents were used to calculate the weights (W_i) of these environmental impact indicators through the following equations (Eq.(5) and Eq.(6))(Lim and Biswas, 2018).

$$Wj = nj1 * 1 + nj2 * 2 + nj3 * 3 + nj4 * 4 + nj5 * 5 \tag{5}$$

$$Wi = Wj/W_{tot} * 100 \tag{6}$$

j = 1, 2, 3….M (environmental impact indicator)
nj1 = no. of ‘no responses’ for j
nj2 = no. of ‘somewhat important’ responses for j
nj3 = no. of ‘moderately important’ responses for j
nj4 = no. of ‘important’ responses for j
nj5 = no. of ‘very important’ responses for j
W_{tot} = sum of all weights (W_j) for M number of indicators

The Australian indicator set with embodied energy V2.01 was utilised to calculate indicators of land use, water use, eutrophication, global warming potential (GWP), and cumulative energy demand (CED). Additionally, the acidification potential and abiotic depletion potential (ADP) were calculated using the EPD (2013) V1.02 method, while the photochemical smog and particulate matter were determined using the ILCD 2011 Midpoint+ V1.08 method. The eco-toxicity was assessed by using the CML-IA baseline V3.03 method.

Life cycle cost (LCC) – the life cycle cost (LCC) method was used to calculate the economic impacts of AM parts with a similar goal, scope, and LCI as the ELCA (Kicherer et al., 2006). The functional unit was '*the cost of delivery of fluid during the service life of the impeller'*. The costs were calculated according to the AS/NZS 4536:1999 standard (Standards Australia/ Standards New Zealand, 1999). The LCI values were converted into corresponding cost values using market data.

The costing model included two stages. The first stage is to calculate the LCC of impeller production to determine the price of impeller. The second stage is to calculate the LCC of pump use. This has been included in Section 2.4 of **article 2 – Appendix B**.

- Stage 1 – LCC of impeller production

The first step included the costs from the design stage to manufacturing stage in terms of capital, labour, energy use, and transportation (Eq.(7)). The design stage costs comprise of utility costs related to product design and process design (Payscale, 2020). The material processing costs comprise of the cost of the material, as well as transportation costs incurred in delivering material to the AM facility located in Australia (Australian Government, 2015). The costs associated with the manufacturing stage were capital costs, energy costs (Canstar Blue, 2020), and labour costs (Australian Bureau of Statistics, 2018), which were allocated based on the print time for each impeller. The production of the AM impeller was assumed to take place in a mass production scenario, considering the expected lifetime of the 3D printers. Similarly, SM impeller, considered the expected lifetime of the CNC machines. The life cycle cost (LCC) calculation was performed using an inflation rate of 1.90% and a discounting factor of 7% (Trading Economics, 2020).

The life cycle cost (LCC) of production per impeller was determined by the costs incurred in each stage, from design to manufacturing, which were first converted into present values (PV) and then added together. The PV was then multiplied by a capital recovery factor (CRF) and divided by the production output (PO) to obtain the LCC of impeller production (Simplified in Eq.(7)). The market price of the impeller (PI) was calculated by adding a profit margin (PM) of 35% to the LCC of impeller production (Plumbing and Mechanical, 2000)(Eq.(8)).

$$LCC_{Impeller,prod.} = (PV_{Capital} + PV_{Labour} + PV_{Energy} + PV_{O\,\&\,M}) \times CRF/PO \qquad (7)$$

$$PI = LCC_{Impeller.prod.} \times (1 + PM) \qquad (8)$$

- Stage 2 – LCC of pump use

The LCC of pump use includes the costs of AM part in the functional application. The LCC of pump use during the impeller service life (SL) ($LCC_{P,SL}$) was calculated using the PV of PI, which was multiplied by CRF and then divided by SL of the impeller as presented in Eq.(9).

$$LCC_{P,SL} = (PV_{PI}) \times CRF/SL \tag{9}$$

Step 4 – Eco-efficiency (EE) portfolio analysis

The life cycle environmental impacts (LCEI) and life cycle costs (LCC) were incorporated into the eco-efficiency (EE) portfolio analysis to determine eco-efficient options and identify hotspots to implement improvement strategies. This has been included in Section 2.5 of **article 2 – Appendix B**. The LCEIs of pump impeller 'n' were normalised (Eq.(10)) by dividing with the relevant $GDEI_i/Inh$ to obtain the normalised value of environmental impact ($NEI_{i,n}$)(Bengston and Howard, 2010, Department of the Environment and Energy, 2019). The $NEI_{i,n}$ was multiplied by the corresponding weights (W_i) for each impact 'i' (Eq.(11)) to obtain the sum of environmental impacts (EI_n) for impeller 'n'.

$$NEI_{i,n} = \frac{LCEI_{i,n}}{GDEI_i/Inh} \tag{10}$$

$$EI_n = \sum_{i=1}^{11} NEI_{i,n} \times W_i \tag{11}$$

The life cycle costs (LCC_n) of pump impeller 'n' were normalised (Eq.(12)) by dividing with the relevant GDP/Inh to obtain the normalised costs (NC_n).

$$NC_n = \frac{LCC_n}{GDP/Inh} \tag{12}$$

The portfolio positions (Eq.(13) and Eq.(14)) of impellers were calculated by dividing the EI and NC of each impeller by average EI and average NC of all impellers.

$$PP_{e,n} = \frac{EI_n}{\sum EI_n/j} \tag{13}$$

$$PP_{c,n} = \frac{NC_n}{\sum NC_n/j} \tag{14}$$

The $R_{E/C}$ is the ratio between average EI and average NC (Eq.(15)). The $R_{E/C}$ was used to obtain the improved portfolio positions ($PP'_{e,n}$, $PP'_{c,n}$) (Eq.(16)) (Arceo et al., 2019). These were plotted in the EI_n vs. NC_n graph (Figure 3.4).

$$R_{E/C} = \frac{\sum EI_n/j}{\sum NC_n/j} \tag{15}$$

$$\mathrm{PP'}_{\mathrm{e,n}} = \frac{\left[\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j} + \left[\mathrm{PP}_{\mathrm{e,n}} - \left(\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j}\right)\right] \cdot \sqrt{\left(\mathrm{R}_{E/C}\right)}\right]}{\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j}} \tag{16}$$

$$\mathrm{PP'}_{\mathrm{c,n}} = \frac{\left[\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j} + \left[\mathrm{PP}_{\mathrm{c,n}} - \left(\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j}\right)\right] / \sqrt{\left(\mathrm{R}_{E/C}\right)}\right]}{\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j}} \tag{17}$$

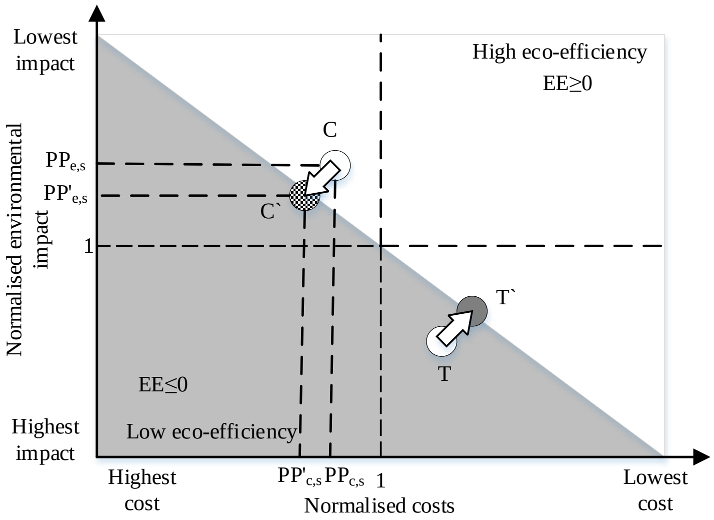

Figure 3.4: EE portfolio and positions (**Article 2 – Appendix B**)

The eco-efficiency method by BASF was used for the eco-efficiency portfolio analysis. The value of eco-efficiency is denoted by the perpendicular length above the diagonal line. Impellers that were positioned below the diagonal line were considered not eco-efficient, requiring additional environmental and economic improvements.

Step 5: Hotspot analysis for selecting the eco-efficient option

This involves the cause diagnosis using ELCA and LCC to find any environmental and economic problematic issues (hotspots), requiring technological improvements. This has been further explained in **Article 2 – Appendix B**. Once the improvement strategies have been considered, LCI has been revised to conduct follow-up ELCA and LCC to determine the improved EE portfolio positions. For example, hotspot analysis revealed that the material processing stage of virgin polymer composites contributed significantly to the LCEI of AM parts. Therefore, the eco-efficiency improvement strategy of the use of recycled feedstock for AM has been considered. The study has used pre-consumer polylactic acid (PLA) waste from AM as the feedstock for TEE assessment. Figure 3.5 shows the manufacturing process flow diagram of recycled feedstock material for AM application.

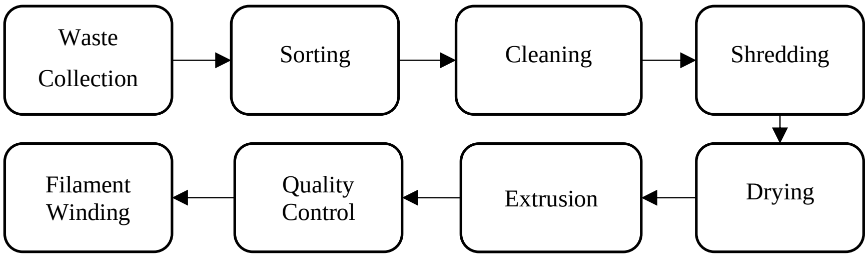

Figure 3.5: Recycled filament manufacturing process (**Article 4 – Appendix D**).

The techno-eco-efficiency framework assessed whether the AM parts made of recycled material are technically, environmentally, and economically feasible. A similar technical feasibility assessment, ELCA, LCC, and EE assessment were conducted for the recycled plastic AM parts to determine the techno-eco-efficiency in comparison with virgin plastic AM parts.

Step 6 – Social life cycle assessment (SLCA)

Once the options were found to be technically, economically, and environmentally feasible, the social impacts of techno-eco-efficient options were assessed using an SLCA, in line with the triple bottom line objectives of sustainability. A similar goal, scope, and LCI as the ELCA and LCC were used in the SLCA, in line with the United Nations Environmental Programme (UNEP) guidelines.

This study employs a quantitative approach of assessing social impacts on stakeholders of employees, local community, and society, using data from LCI. The indicators of health and safety, as well as employment level, were investigated under social impacts on employees. The indicators of conservation of natural resources and reduction of landfill were investigated under social impacts on the local community and society.

Health and safety – the assessment of the health and safety of employees involved in AM is a crucial parameter for evaluating the social impacts associated with AM. The human toxicity potential (HTP) can be used to measure the toxicity levels stemming from inhalation, ingestion, and dermal contact within the mass manufacturing scenario of AM. In this study, the HTP by inhalation was calculated using Eq. (18). TP_a is the toxicity potential to air, while m_a is the mass of particulate matter emission. The TP_a for PLA is 620 kg 1,4-DB eq./kg PLA.

$$HTP = m_a \times TP_a \tag{18}$$

The HTP of design to use stages of the impeller has been calculated as follows (Eq. (19)).

$$HTP = HTP_{Design} + HTP_{Processing} + HTP_{Mfg} + HTP_{Use} \tag{19}$$

Employment level – the change in the level of employment due to the change in the manufacturing strategies has been calculated in terms of the number of hours of labour, The number of labour hoursin AM were compared with the number of hours of labour for the same product in SM or injection moulding (Eq.(20)).

$$Employment\ level = \frac{No.of\ hrs.of\ labour\ in\ SM\ or\ IM\ - No.of\ hrs.of\ labour\ in\ AM}{No.of\ hrs.of\ labour\ in\ SM\ or\ IM} \times 100 \quad (20)$$

The following two indicators are based on the intergenerational social equity aspect (Biswas and John 2022), which is to conserve resources for the future generation.

Conservation of natural resources – the social impacts on the conservation of natural resources were calculated from the resource consumption data in LCI (Section 2.3.4 in **article 4** (**Appendix 1**)), as follows (Eq.(21)).

$$Material\ conservation = \frac{Primary\ material\ for\ SM\ or\ IM - Primary\ material\ for\ AM}{Primary\ material\ for\ SM\ or\ IM} \times 100 \quad (21)$$

Reduction of landfill – the social impact of the reduction in landfill was calculated by the amount of material recycled in the mass AM scenario. This was benchmarked against the landfill required to manage 7,000 tonnes of waste in Western Australia over 60 years (Eq.(22)).

$$Reduction\ of\ landfill\ (ha) = \frac{Mass\ of\ material\ recycled}{7000\ t} \times 64\ ha \qquad (22)$$

This study did not evaluate other social impacts, such as work intensity, occupational accidents, and skill development, due to the limited availability of data, the social context, and for expert judgment.

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CHAPTER 4 TECHNO-ECO-EFFICIENCY ASSESSMENT OF VIRGIN POLYMER COMPOSITE IMPELLERS

4.1 Introduction

The aim of this chapter is to assess the technical feasibility and eco-efficiency of virgin polymer composites using the developed techno-eco-efficiency (TEE) framework. Firstly, the chapter covers the technical feasibility assessment of virgin polymer composite AM parts. Secondly, the environmental impact assessment and life cycle costing of technically feasible virgin polymer composite AM parts were conducted to assess the eco-efficiency performance.

The findings of this chapter were published in the article entitled ‘Techno-eco-efficiency assessment of additive and subtractive manufactured parts: An application of life cycle assessment’, which has been included in **Article 2 – Appendix B**.

4.2 Application of TEE framework to virgin polymer composites

The developed TEE framework was used to evaluate the techno-eco-efficiency performance of virgin polymer composite AM pump impellers in comparison with conventional SM pump impellers.

Step 1: Parts, materials, processes selection

The selection criteria for parts, materials, and processes have been described in Section 2.2.1 of **article 2** (**Appendix B**). A semi-open pump impeller from a *Grundfos Unilift KP250* pump was considered for the techno-eco-efficiency assessment of pump impellers. AM pump impellers were fabricated through the fused filament fabrication (FFF) process using a *Markforged Mark 2* 3D printer. A carbon fibre-nylon composite material (*Onyx*) was used to manufacture these impellers. A glass fibre material was used as the reinforcement material in the composite. Conventional nylon (PA6) material was used as the SM benchmark.

Step 2: Technical feasibility assessment of virgin polymer composites

The methodology for the technical property and performance testing has been described in Section 2.2.2 of **article 2** (**Appendix B**). The technical feasibility assessment revealed that dimensional tolerances and surface roughness of all AM parts were within acceptable levels. The solid, 50% triangular, and 50% hexagonal pump impellers showed lower tensile properties. Similarly, lower fatigue properties were observed due to lower ultimate tensile strength (UTS) values.

However, the pump impeller with fibre reinforcement showed better tensile and fatigue results compared to the SM (N) benchmark. Since the fatigue life of the AM pump impeller was found to be superior to SM impeller benchmark, the service life of the AM impeller was estimated from market data, based on wear and corrosion.

Fracture surface analysis revealed that the cracks progressed in the direction of the print lines on the surface. Further, the geometry of the internal structure influenced the propagation of the cracks, with the presence of voids, defects, and porosity between the layers, intensifying the problem. However, the incorporation of continuous fibre reinforcement in the F specimen contributed to better tensile and fatigue properties.

The density analysis revealed a variation of 1.67% between the density of the AM material and that of the Onyx material, which confirmed the presence of voids, defects, and porosity in the AM impellers. Additionally, a comparison was made between the hydraulic performance of the AM impellers and the OEM impeller, with the former exhibiting slightly inferior performance due to its higher surface roughness (He et al., 2019, Fernández et al., 2016).

The study evaluated the technical feasibility of different pump impellers and found that only the fibre-reinforced impeller met all the required technical properties. Therefore, it was considered for the EE stage of the TEE framework.

4.2.1 Environmental life cycle assessment (ELCA)

The ELCA of a technically feasible fibre-reinforced pump impeller was carried out for the EE analysis. Following the ISO 14040/44 standards (International Organisation for Standardization, 2006), the environmental impacts of the impeller were determined. The functional unit of the ELCA was '*one impeller delivering fluid over its useful service life*'. The scope of the ELCA and the selection of environmental impact indicators and weights through consensus survey have been described in Section 2.3 of **article 2** (**Appendix B**).

The ELCA analysis showed that the LCEI values of the AM (F) impeller were lower than those of the SM impeller. The production stage of the SM (N) impeller was found to have the highest environmental impact due to the high material and energy consumption associated with aluminium and steel processing in CNC machines. In contrast, the electricity consumption during the production of the AM (F) impeller was identified as the major contributor to environmental impacts, resulting in CO_2, SO_x, and NO_x emissions from the combustion of black coal and natural gas. Moreover, the material processing stage also contributed significantly to environmental impacts, primarily due to water-intensive carbon-nylon composite production and the release of plastics into aquatic ecosystems.

4.2.2 Life cycle costing (LCC)

The methodology for life cycle costing (LCC) has been presented in Section 2.4 of **article 2** (**Appendix B**). The life cycle cost of the pump impeller was calculated in two stages. Firstly, the life cycle cost of impeller production was calculated from the material extraction stage to the manufacturing stage. Secondly, the life cycle cost of the pump use stage was calculated by incorporating the life cycle cost of impeller production as a capital cost. Table 4.1 presents the results of the LCC of the pump impeller over the service life.

Table 4.1: LCC of pump usage for virgin polymer composites (**Article 2 – Appendix B**)

	PV_{PI} (AUD)	**Annuitised cost (AUD)**	**$LCC_{P,\,SL}$ (AUD)**
F impeller	61.27	154.28	64.28
N impeller	220.15	554.39	231.00

The PI of the AM (F) impeller was found to be 82.5% lower than that of the SM (N) impeller, which can be attributed to its lower capital, replacement, and manufacturing costs. The manufacturing stage was found to have the greatest impact on the PI, with high labour costs being a significant factor for both the N and F impellers. Even though conventional nylon is cheaper than polymer composites, the N impeller has higher cost values due to the materials wasted during SM. Additionally, the operating cost of the F impeller is higher than that of the N impeller due to its lower pumping performance, resulting in a 2% increase in energy consumption during pump usage. Finally, the LCC of pump use for F impeller is 71% lower than the N impeller.

4.2.3 Eco-efficiency (EE) assessment

The methodology for eco-efficiency (EE) assessment has been described in Section 2.5 of **article 2** (**Appendix B**). Based on the results, it can be concluded that both the N and F impellers demonstrated positive eco-efficiency. However, the F impeller displayed higher eco-efficiency than the N impeller. This higher eco-efficiency in the F impeller can be attributed to factors such as lower material consumption, energy consumption, labour costs, and environmental impacts. The eco-efficiency portfolio aims to determine the most eco-efficient option, which is the AM fibreglass reinforced (F) impeller.

4.3 Conclusion

The TEE framework was successfully deployed to assess the techno-eco-efficiency of virgin polymer composite AM materials. The study found that the fibre-reinforced pump impeller (F) was technically feasible for the application of industrial wastewater pumping, in comparison to a conventional SM impeller and OEM impeller. The service life estimated from the technical feasibility assessment was integrated into the EE assessment.

The results of the ELCA found that the total environmental impact of AM (F) impeller was 96% lower than the SM (N) impeller. The results of the LCC found that the normalised cost of the F impeller was 71% lower than the SM (N) impeller. Hence, the EE analysis identified that AM (F) impeller shows comparatively higher positive eco-efficiency. As a result, the fibreglass-reinforced AM impeller (F) was proved to be a techno-eco-efficient product.

The techno-eco-efficiency framework could be employed in the decision-making process in the manufacturing industry, for the selection of technically feasible, economically viable, and environmentally benign parts. The application of AM pump impellers in the study serves as a validation of the techno-eco-efficiency framework and establishes additive manufacturing as a sustainable manufacturing strategy.

4.4 References

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CHAPTER 5 TECHNO-ECO-EFFICIENCY ASSESSMENT OF METAL IMPELLERS

5.1 Introduction

The aim of this chapter is to assess the technical feasibility and eco-efficiency performance of metal impellers using the techno-eco-efficiency framework. Firstly, the chapter examines the technical properties and performance assessment of metal AM parts. Subsequently, the chapter integrates the findings of environmental impact assessment and life cycle costing for the eco-efficiency assessment of technically feasible metal AM parts.

The findings of this chapter were published in the article entitled 'Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining' (**Article 3 – Appendix C**).

5.2 Application of TEE framework to metals

Since metals are widely used for functional applications (Thompson et al., 2019), the techno-eco-efficiency framework developed in this study was employed to evaluate the technical feasibility and eco-efficiency of metallic additive manufacturing (AM) parts relative to subtractive manufacturing (SM) parts.

Step 1: Parts, materials, processes selection

A semi-open centrifugal pump impeller from a *Grundfos Unilift KP-250* pump was selected as the most feasible product from a product portfolio evaluated with a multi-criteria feasibility score model to assign a feasibility score (Section 2.1 in **article 2 – Appendix B**). The *Desktop Metal* Studio was chosen as the metal 3D printer for its innovative metal extrusion additive manufacturing process, which allows the production of AM metal parts with comparable properties to those manufactured through metal injection moulding (Optimim, 2021). The SM processes of CNC machining operations (turning, milling, drilling) were selected for the SM part.

From the material portfolio available for the 3D printer (Desktop Metal, 2020), the 316L stainless steel material was chosen due to its similarities to the 304 stainless steel material utilised in the pump impeller from OEM. The 316L stainless steel material exhibits improved mechanical properties across a broad temperature range and exceptional corrosion resistance, which renders it an ideal choice for impellers designed to operate under harsh environmental conditions.

Step 2: Technical feasibility assessment of metals

The technical feasibility of AM parts was examined in the first step of the TEE framework (Section 3.1 in **article 3 – Appendix C**). The AM part exhibits a relatively higher surface roughness in comparison to the SM part. Specifically, higher surface roughness was observed in the vanes of the AM impeller, owing to uneven surface texture in the Z direction stemming from the inherent characteristics of print layers. Conversely, in the SM part, the surface roughness of the shroud is elevated due to residual cuts from the end milling cutting tool that cause a non-uniform surface texture. The post-processing of the parts could improve the surface roughness of AM and SM parts significantly, but no post-processing methods were considered, as this study only focused on the comparison of the two manufacturing processes.

The density of the AM specimen has been measured to be 97.8%, which is similar to that of the bulk material. This indicates that the sintering process has effectively removed any voids within the material, resulting in a solidified 3D printed material. The tensile strength of the AM material is also similar (92.8%) to that of the bulk material at an acceptable level (Jiang and Ning, 2021). The fatigue strength of the AM material has slightly decreased (81.6%) due to its lower tensile strength compared to the SM material (Sadaf et al., 2021). However, the fatigue life of the metal AM impeller exceeded the fatigue limit under steady operating conditions. Therefore, the service life was estimated based on the available market data, accounting for wear, foreign object damage, corrosion, and cavitation. It was observed that the metal AM impeller’s hydraulic performance surpasses that of the OEM impeller. Overall, the technical feasibility assessment indicates that a metal AM pump impeller is viable for a functional application.

Step 3: Eco-efficiency (EE) assessment

Environmental life cycle assessment (ELCA) – since both the AM and SM parts were found to be technically feasible based on the results of the technical feasibility assessment, they were subjected to an environmental life cycle assessment to evaluate their respective environmental impacts. The metal AM impellers displayed higher LCEI values for GWP, eutrophication, land use, water use, ADP, acidification, particulate matter, and photochemical smog, while SM impellers had higher LCEI values for eco-toxicity (Peng et al., 2017). The high eco-toxicity could be caused by the significant amounts of metallic waste and cutting fluids generated in SM. The cumulative energy demand of metal AM was identified as an environmental hotspot, which is due to the high energy consumption during the metal sintering process.

Life cycle costing (LCC) – the results indicate that the use of a metal AM impeller is considerably 1.78 times more expensive than the use of an SM impeller. This could be due to the high equipment cost of metal AM, which is approximately 4.25 times higher than the cost of CNC machining equipment, resulting in high capital costs (Thompson et al., 2019). Conversely, the additive nature of metal AM technology has reduced the amount of material waste, resulting in lower production costs for the AM impeller. The material costs are one-third lower than those of the SM impeller. SM requires removing a large amount of material, resulting in high material costs for the SM impeller.

Eco-efficiency (EE) portfolio analysis – the results indicated that the AM impeller exhibits higher eco-efficiency, while the SM impeller exhibits lower eco-efficiency. This eco-efficiency can be primarily attributed to the AM impeller's significantly lower normalised environmental impact (54.6%) compared to the SM impeller. The lower normalised environmental impact of the metal AM part outweighs the economic losses (43.8%) in order to become eco-efficient. The additive nature of metal AM technology results in minimal material wastage, which contributes to lower environmental impact and less resource consumption. Therefore, despite the initial cost differential, metal AM technology proves to be a more eco-friendly and sustainable manufacturing method for impellers.

5.3 Conclusion

Metal additive manufacturing (AM) has emerged as a promising technology for producing complex geometries with high accuracy and efficiency, and is increasingly being used across various industries. However, the environmental impact of metal AM processes has been a subject of concern due to the high energy consumption and high cost of production. This study aimed to address this issue by evaluating the techno-eco-efficiency performance of metal AM impellers in comparison with metal SM impellers. The metal AM impeller was found to be technically feasible for the functional application of wastewater pumping, in comparison to the metal SM impeller.

The ELCA of the metal AM impellers has shown 54.6% lower environmental impacts compared to the SM benchmark. However, the life cycle cost of the metal AM impeller was found to be 43.8% higher than the SM benchmark. This is due to the high capital costs in metal AM. The Metal AM was found to be eco-efficient in comparison to the metal SM impeller.

Metal additive manufacturing could be successfully utilised by the manufacturing industry as a technically feasible and eco-efficient alternative to conventional manufacturing, as evidenced by the study. The techno-eco-efficiency framework developed in this study could be used as a decision support tool for the assessment of metallic materials and functional parts, facilitating the adoption of sustainable manufacturing strategies.

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CHAPTER 6 TECHNO-ECO-EFFICIENCY AND SOCIAL ASPECTS OF RECYCLED PLASTIC IMPELLERS

6.1 Introduction

The aim of this chapter is to assess the technical feasibility, eco-efficiency, and social aspects of recycled plastic materials through the techno-eco-efficiency framework. Firstly, the chapter presents the technical properties and performance assessment of recycled plastic AM parts. Secondly, it discusses the use of environmental impact assessment, and life cycle costing, and for assessing the eco-efficiency of technically feasible recycled plastic AM parts. Finally, the social implications of technically sound eco-efficient options are presented.

The findings of this chapter were published in the article entitled ‘Additive manufacturing of recycled plastics: A techno-eco-efficiency assessment’, which has been included in **Article 4 – Appendix D**.

6.2 Application of TEE framework to recycled plastics

The study on virgin polymer composites exhibited that the material processing stage contributes to the highest environmental impact of AM part (Jayawardane et al., 2021). Therefore, the eco-efficiency improvement strategy of material recycling and the use of recycled feedstock AM material was considered in this study. The TEE framework has the flexibility to incorporate changes from the use of improvement strategies and to calculate the revised eco-efficiency portfolios of parts made through recycled feedstock material.

Step 1: Parts, materials, processes selection

A semi-open impeller in a centrifugal Grundfos Unilift KP-250 water pump was selected as the case study for the implementation of the TEE framework. The pre-consumer waste generated during virgin PLA AM filament manufacturing was used to manufacture the recycled PLA (RPLA) filament material. A virgin PLA (VPLA) impeller was used as the benchmark for technical feasibility and eco-efficiency comparison. The impellers were manufactured using fused filament fabrication technology by the MakerBot Replicator Z18 3D printer.

Step 2: Technical feasibility assessment

The technical feasibility of pump impellers made from RPLA material was assessed in comparison with VPLA material. An injection moulded PLA (IMPLA) material was used as the bulk material benchmark. The results have been included in Section 3.1 in **article 4 – Appendix D**. The technical performance of RPLA specimens was found to be slightly lower than the VPLA and IMPLA specimens. The lower density and hardness of the AM specimen may be attributed to the high porosity, defects, and voids present in the recycled AM materials. The ultimate tensile strength (UTS) of the RPLA specimen was observed to be 10.5% lower than that of the VPLA specimen, which in turn resulted in a 15.4% reduction in the fatigue strength of the RPLA specimen. Although the service life of the RPLA impeller has been reduced due to lower estimated fatigue life, the RPLA impellers displayed superior hydraulic performance compared to the OEM impeller, which can be attributed to the lower weight of the impeller.

The disadvantage with having a lower service life of RPLA impellers can be offset by its lower life cycle costs and environmental impacts. Therefore, RPLA impellers have been considered technically feasible, with multiple impellers to match the service life of the benchmark.

Step 3: Eco-efficiency (EE) assessment

Eco-efficiency of technically feasible RPLA impellers has been investigated through environmental life cycled assessment (ELCA) and life cycle costing (LCC) methods.

Environmental life cycle assessment (ELCA) – the results of ELCA demonstrate that the RPLA impellers have lower life cycle environmental impacts (LCEI), compared to the VPLA impellers, except for abiotic depletion potential (ADP). The reduced service life of the RPLA impeller has required the use of multiple impellers (2.8) during the service life of one VPLA impeller, which has increased the ADP by 17.9%.

Life cycle costing (LCC) – the RPLA impeller has been found to have significantly higher total life cycle costs than the VPLA impeller (Table 6.1). This has been attributed to higher capital costs and use stage costs due to the lower service life of the RPLA impeller.

Table 6.1**:** LCC of pump usage for RPLA (**Article 4 – Appendix D**)

	$PV_{total, P}$ (AUD)	**Annuitised cost (AUD)**	**$LCC_{P, SL}$ (AUD)**
RPLA	89.92	148.51	685.45
VPLA	66.33	109.55	180.09

Eco-efficiency (EE) portfolio analysis – the EE portfolio analysis showed that the RPLA impeller is eco-efficient while the VPLA impeller is not eco-efficient. This is because of the fact that the RPLA impeller exhibited a lower normalised environmental impact, which is 93% of the environmental impact of the VPLA impeller and offsets its higher normalised costs. The normalised cost of the RPLA impeller is 74% more than the VPLA impeller. These results demonstrate that the recycling of material for additive manufacturing can substantially reduce the environmental impacts of the manufacturing process by 93% for each dollar invested in recycling.

Step 4: Social life cycle assessment (SLCA)

The social impacts of techno-eco-efficient options have been evaluated through an SLCA approach, following the same scope and LCI of ELCA and LCC methods (Naghshineh et al., 2020).

Health and safety – the findings revealed that the RPLA impeller could reduce the human toxicity potential (HTP) by decreasing the emission of particulate matter into the air during the additive manufacturing process, thereby maintaining HTP below the threshold value (30 HTP/ 0.015 mg.m^{-3} for PM2.5) (Ma et al., 2018). Such reduction in HTP can potentially lead to favourable socio-economic outcomes, including lower costs associated with compensation and healthcare, avoidance of downtime, and improved productivity.

Employment level – the results demonstrated that AM processes had led to a reduction of employment levels, compared to IM and SM. However, recycled AM processes exhibit a higher employment level compared to virgin AM, as more labour hours are required to address any unforeseen issues in setup, configuration, repair, and monitoring of equipment, when using recycled material feedstock (Naghshineh et al., 2021).

Conservation of natural resources – the results show that the RPLA impeller reduces material consumption by 12.8% compared to IMPLA impeller and 92.5% compared to SM impeller. These results demonstrate that there is a significant potential for AM and material recycling in reducing virgin PLA production and easing the burden on food production, specifically on sugar cane and corn starch that are used for PLA production. Furthermore, replacing VPLA impellers with RPLA impellers could result in a reduction of 91% of the total energy consumption. These efforts can contribute to resource conservation for future generations and enhance intragenerational social equity.

Reduction of landfill – the annual material consumption for the mass production of pump impellers is estimated to be 101.2 kg. As a result, an industrial manufacturer utilising a single 3D printer for pump impeller production could potentially reduce 9.25E-04 hectares of landfill. Additionally, the ELCA conducted in the study also revealed that RPLA impellers could result in a 96.8% reduction in land use compared to VPLA impellers. The utilisation of waste PLA for AM not only minimises the generation of harmful toxins and leachate from landfills, but also leads to a decrease in required landfill area, thereby conserving land for future generations.

6.3 Conclusion

The technical feasibility assessment results showed that the RPLA impeller had a significantly shorter estimated service life compared to the VPLA impeller due to its lower density, ultimate tensile strength, and fatigue strength. However, the RPLA impeller demonstrated higher hydraulic performance in the hydraulic performance test than the OEM part, for which RPLA parts were deemed as technically feasible.

The ELCA results showed that the RPLA impeller lowers environmental impacts but increases life cycle costs, in comparison to the VPLA impeller. The eco-efficiency assessment revealed that recycled materials improve the eco-efficiency of virgin plastic AM. The social impact assessment showed positive impacts on employee health and safety but negative impacts on employment levels. The study also found that the use of recycled materials could significantly reduce virgin PLA production and landfill area.

The eco-efficiency improvement strategy of the use of recycled feedstock for AM has been successfully implemented to address the identified hotspot of higher environmental impact in the material processing stage. The follow-up TEE assessment revealed that the use of recycled plastic material in AM is more techno-eco-efficient, in comparison to virgin plastic materials and injection moulded materials. Further, the social impact assessment of AM parts showed several positive and negative social impacts, which assisted in the integration of triple bottom line objectives of sustainability for assessing AM parts through the TEE framework.

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CHAPTER 7 CONCLUSION

7.1 Introduction

This concluding chapter presents a summary of the thesis, highlighting the cohesive nature of publications aimed at addressing the overarching goal while fulfilling distinct research objectives. Central to this study is the ‘techno-eco-efficiency’ framework, developed to effectively evaluate the techno-eco-efficiency performance of additive manufactured parts compared to subtractive manufactured parts.

Each publication generated from this PhD work contributes to a cohesive narrative by addressing specific research objectives. The first publication conducted an in-depth exploration of the existing body of knowledge, identifying critical research gaps subsequently addressed in this thesis. The second publication served as the foundation to establish the techno-eco-efficiency framework and provided context with virgin polymer composite materials. The third publication validated the established framework with a novel metal additive manufacturing technology. Finally, the fourth publication focused on the techno-eco-efficiency improvement strategies and examined the social implications of techno-eco-efficient options.

This chapter interprets how the research objectives were successfully achieved through the comprehensive synthesis of the publications. By strategically interconnecting these research works, this thesis makes a substantial contribution to the advancement of knowledge in the realm of techno-eco-efficiency assessment for additive manufacturing processes.

7.2 Outcomes of research objectives

The following research objectives have been achieved in the research study.

Reviewing the state of the art of technical feasibility assessment methods and sustainability assessment methods used for additive and subtractive manufactured parts

Several studies have assessed the sustainability performance of AM parts, assuming that they possess similar technical performance as SM parts.

The review confirms that AM parts exhibit inherent anisotropy in microstructure due to the additive nature of their manufacturing process, whereas SM parts retain isotropic material properties. Also, the technical feasibility of AM parts in functional applications has been identified as a crucial consideration in a sustainability assessment framework for comparison purposes. The techno-eco-efficiency (TEE) framework has addressed this issue by incorporating the technical feasibility assessment prior to evaluating the eco-efficiency performance.

The review confirms that the technical properties and performance of AM parts play a significant role in determining reliability, durability, and service life in the functional applications. The changes in the service life of a part can result in overestimation or underestimation of its sustainability performance, which has been identified as a critical consideration in LCA tools. The techno-eco-efficiency framework has addressed this concern by determining the fatigue life of parts to estimate their service life in functional applications. This framework has integrated technical feasibility into sustainability performance by considering the estimated service life of the part in the functional unit of both ELCA and LCC tools.

In the conventional approach to sustainability, several studies have evaluated the environmental, economic, and social impacts of products separately, but the integration of these three pillars was found to be indispensable for a comprehensive sustainability assessment framework to support the decision-making process.

A growing interest in eco-efficiency analysis has recently been found, as this analysis emerged as a promising methodology by combining the environmental and economic pillars of sustainability. ELCA and LCC have been found to be the widely used tools to evaluate the environmental and economic performance of products. The techno-eco-efficiency framework used is relatively new and has not been applied in the manufacturing sector. Also, technical feasibility has not been incorporated into the eco-efficiency framework. This study combines the results of technical feasibility, ELCA, and LCC for TEE analysis to identify techno-eco-efficient options.

The literature on sustainability performance assessment of AM and SM parts has given limited attention to the social impacts of manufactured parts. This study aims to assess the social impacts of techno-eco-efficient options using a Social Life Cycle Assessment (SLCA) approach, which takes into account the same goal, scope, and life cycle inventory used in the ELCA and LCC tools.

Furthermore, the eco-efficiency analysis has been found to demonstrate its suitability for incorporating improvement strategies, owing to its ability to identify environmental and economic hotspots. In this study, the material recycling strategy has been identified as the eco-efficiency improvement strategy in AM to further enhance the TEE performance.

Assessing the technical properties and performance of additive and subtractive manufactured parts

The 'techno-eco-efficiency' (TEE) framework was developed to address the research gaps identified from the literature review. The techno-eco-efficiency performance of AM parts was compared with SM parts using this framework to identify the most techno-eco-efficient option to support the decision-making process. The evaluation of technical feasibility was based on the assessment of engineering properties and functional performance.

The study found that all AM impellers produced using virgin polymer composite material had acceptable surface roughness and dimensional tolerances. However, only the fibre-reinforced AM (F) impeller demonstrated technically feasible performance. Impellers with solid infill, 50% triangular infill, and 50% hexagonal infill exhibited lower tensile and fatigue properties when compared to the conventional nylon 6 benchmark.

In the context of metal AM, the study found that metal AM impeller exhibit comparable technical properties in terms of surface roughness, dimensional tolerance, and product density. The tensile properties of metal AM impeller were slightly reduced, which was also seen in fatigue properties. However, it was found that metal AM impeller could withstand more than 10^6 fatigue cycles under the fatigue loading of 10 MPa. The metal AM impeller also showed higher hydraulic performance compared to the OEM impeller. Therefore, metal AM impeller was considered technically feasible in comparison with metal SM impeller.

Assessing the environmental impacts and life cycle costs using ELCA and LCC tools

The replacement of SM nylon impeller with the fibre-reinforced nylon AM impeller (F) significantly reduces the total environmental impact (96%), mainly due to the reduction in material and energy during the additive manufacturing process.

The fibre-reinforced impeller exhibits a 71% life cycle cost in comparison to the SM nylon impeller, owing to reduced labour costs. These findings suggest that additive manufacturing of polymer composite parts can significantly mitigate the environmental impacts and associated costs by replacing SM processes.

The metal AM impeller showed lower LCEI in eco-toxicity compared to the metal SM impeller, which could be due to metallic waste combined with cutting fluids generated by SM. Further, metal AM has been found to exhibit higher environmental impacts in terms of cumulative energy demand, mainly due to the energy-intensive sintering process that accounted for 84% of the cumulative energy demand. Overall, the LCEI of the AM impeller is 55% lower than the SM impeller due to a higher reduction (98%) of eco-toxicity impacts.

The metal AM pump impeller was 1.78 times more expensive than the metal SM impeller due to having higher material and equipment costs associated with the novel metal AM technology.

Integrating the technical, environmental, and economic impacts of manufactured parts through the techno-eco-efficiency framework

The TEE analysis for virgin polymer composites confirmed that both SM nylon and fibre-reinforced AM impellers showed positive eco-efficiency, while the latter is more eco-efficient than the former due to having lower material consumption, energy consumption, labour costs, and environmental impacts compared to the SM benchmark. In the case study of a centrifugal impeller in the industrial and domestic waste-water pumping application, the virgin polymer AM part lowered the environmental impacts and life cycle costs.

The metal AM pump impeller was also found to be more techno-eco-efficient than the CNC machined pump impeller. The effect of higher normalised costs (78%) of AM part has been offset by its lower normalised environmental impact (55%). In the case study of a centrifugal impeller in the industrial and domestic waste-water pumping application, the metal AM part lowered the environmental impacts but increased life cycle costs, while providing the same functional performance as SM part.

The TEE framework distinguishes itself from other LCA methods by providing a comprehensive evaluation that incorporates technical feasibility into eco-efficiency analysis. Additionally, the TEE framework includes the potential to reduce environmental impacts and life cycle costs by identifying hotspots and implementing improvement strategies.

Manufacturing parts from recycled material and assessing the techno-eco-efficiency

Recycled polylactic acid (RPLA) material has been found to be technically feasible in terms of surface roughness and dimensional tolerance. However, the RPLA impeller showed slightly lower density, hardness, UTS, and fatigue strength. The lower technical properties have reduced the estimated service life of the RPLA impellers. However, the RPLA impellers have shown higher hydraulic performance compared to the OEM impeller, which could be due to the lower mass of RPLA impeller. Therefore, it was deemed technically feasible in comparison to VPLA impeller.

The use of RPLA impeller as a replacement for VPLA creates significantly lower environmental impacts by 93%. However, the life cycle costs of the RPLA impeller were found to be higher (74%) than VPLA impeller due to the lower service life of RPLA impeller requiring multiple replacements, and also due to its higher energy consumption in pumping. The use of RPLA materials has been found to offer better eco-efficiency performance compared to VPLA and IMPLA materials due to their lower material and energy consumption in the material processing stage.

Assessing the social impacts of techno-eco-efficient options

The social life cycle assessment has been conducted for stakeholder groups of employees, local community, and society. The results for employees revealed positive social impacts from AM in terms of improved health and safety. The RPLA impeller could reduce the human toxicity potential of manufacturing by 17% compared to the VPLA impeller. However, the employment levels in AM have reduced by 72% compared to SM.

The reduced material consumption in RPLA impellers could conserve natural resources for future generations, which could also enhance intergenerational equity. The mass of material recycled in RPLA impellers amounts to 101.2 kg per annum in a mass manufacturing scenario. The recycling process could divert waste from 9.25×10^{-4} ha of landfill, which could be conserved in a mass AM manufacturing scenario.

7.3 Limitations and recommendations for future work

The manufacturing processes have resulted in socio-economic and environmental consequences that need to be addressed through a structured theoretical framework that provides a comprehensive and holistic assessment of manufactured parts. The research study on integrating technical performance with eco-efficiency plays a pivotal role in improving the triple bottom line sustainability of AM.

The following limitations have been identified in this research study:

- The metal AM in this study was limited to a metal extrusion AM method by *Desktop Metal Studio* 3D printer with stainless steel 316L material. However, the results may differ depending on the materials and the equipment used. Additionally, a newer version of the Desktop Metal Studio printer that eliminates the need for a debinder is recently available, which could further reduce manufacturing time, energy consumption, and the use of chemicals.
- The study also did not consider the failures in mass manufacturing parts as the research mainly focused on the technical feasibility of manufactured impellers. However, there could be a significant rate of product failure due to technical issues, which could be improved in future.
- The variation in hydraulic performance of pump impellers influenced the functional unit of ELCA and LCC, which is the fluid delivery of pump impeller during the service life. The variation was captured though the energy consumption of the pump during the use stage.
- Environmental impact indicators used in this study were selected from a consensus survey with the Australian industry, academia, and government. The environmental

impact indicators would be different for another region and would require indicator selection prior to ELCA. Furthermore, the weighting factors were determined by the consensus of the respondents and could be subjected to bias. The sample size of the survey was designed to minimise the effects of the bias of opinions of respondents.

- The eco-efficiency (EE) analysis involves the normalisation, weighting, and aggregation of environmental impacts obtained from the environmental life cycle assessment (ELCA) analysis to determine a single value of the environmental impact. Nonetheless, the application of economic and environmental data in the analysis could introduce certain uncertainties.
- The mechanical recycling of virgin nylon composites was found to be difficult due to the hygroscopic nature of nylon material and the heterogeneous hybrid structure of fibre-reinforced material. Therefore, an eco-efficiency improvement strategy was conducted for PLA material, which presents similar technical properties compared to nylon material.
- Since this research compared AM and SM strategies, only the parts manufactured by CNC machining processes were compared with AM parts.

The following recommendations could be applied to future work to validate the use of techno-eco-efficiency framework as a decision-support tool for the manufacturing industry.

- Further research could be carried out to evaluate the techno-eco-efficiency of polymer composites reinforced with various materials, such as carbon fibre, and to compare the findings with those of conventional subtractive manufacturing methods.
- Technical feasibility could be assessed with computer numerical simulations and non-destructive testing methods in the future to support the transition to sustainable AM.
- The study suggests implementing strategies to improve the TEE performance of metal AM pump impellers using sintering profile analysis to reduce uneven part shrinkage, improving performance and cost reduction of machines by part integration, replacing non-critical components with cheaper parts, and eliminating equipment idle time.
- Future research could be conducted for a similar techno-eco-efficiency assessment of AM products using recycled stainless steel feedstock material.
- The surface properties of metal AM parts could be further improved by polishing before testing the parts in functional applications.
- Future research could compare the TEE performance of AM parts with other formative manufacturing methods.
- The study suggests that future research should explore the techno-eco-efficiency performance of recycled filament feedstock materials like ABS, PET, and nylon.

Further, the effects of blends of recycled and virgin materials (20% wt., 30% wt., and 50% wt.), fillers, and reinforcement fibres on technical performance and service life could be investigated. Additionally, the benefits of using renewable energy sources for the production of manufacturing parts using recycled materials should also be studied.

- In future research, the SLCA carried out in this study can be expanded by employing a reference scale approach to evaluate qualitative indicators related to social responsibility, fair wages, employment relationships, local employment opportunities, sustainability management, product performance, and end-of-life waste management responsibilities.

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APPENDICES

APPENDIX A – ARTICLE 1

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Authorship agreement

I, Heshan Thenuka Wijerathne Jayawardane, contributed 80% to the paper entitled ‘Sustainability perspectives: A review of additive and subtractive manufacturing.

Mr. H.T.W. Jayawardane

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Author	Signature
Ian J. Davies	
J. R. Gamage	
Michele John	
Wahidul K. Biswas	

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Sustainability perspectives – a review of additive and subtractive manufacturing

Heshan Jayawardane[a,*], Ian J. Davies[b], J.R. Gamage[c], Michele John[a], Wahidul K. Biswas[a]

[a] *Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia*
[b] *School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia*
[c] *Department of Mechanical Engineering, University of Moratuwa, Sri Lanka*

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ABSTRACT

The manufacturing industry contributes to the rapid development of world economy but generates substantial adverse impacts on the environment and society. This research paper explores the tools and methods used to evaluate the sustainability of additive and subtractive manufacturing. A systematic literature review has been conducted to carefully assess literature on part choice, material choice, technical assessment, environmental assessment, economic assessment, social implications, integrations, and sustainability performance comparisons. The study highlights that whilst sustainability performance of additive and subtractive manufactured parts and systems has been assessed, integration of technical feasibility to improve sustainability performance has not been adequately explored. The study concludes that technical feasibility integrated sustainability assessments of additive and subtractive manufactured parts should be followed to bridge the gap between technical and sustainability performance. Further, this review explores challenges to integrate technical and sustainability performance and to improve the overall sustainability aspects of additive and subtractive manufactured parts.

Introduction

The rapid development of the manufacturing processes has significantly influenced the global economy in terms of value addition through increased industrial metabolism. The manufacturing sector contributes 16.96% of global value addition (in comparison to 4.61% for the agriculture sector and 78.43% for the service sector) by converting raw materials to consumable finished goods [1,2]. However, the accelerated level of growth of manufacturing not only generates goods and services but also depletes natural resources and generates waste and emissions which pose adverse impacts on the environment [3]. As of 2021, the manufacturing industry consumes 25% of global energy demand, 40% of global material demand, and produces 20% of global CO_2 emissions [4]. The reduction of energy use, material use, waste, and emissions in industrial manufacturing could significantly improve the global sustainability.

There is an increasing demand for sustainability in modern society due to the increased awareness of climate change, global warming, diminishing natural resources, implications of product usage, and stringent government regulations [5]. The United Nations further emphasises that research on aspects of sustainability is a significant driver to achieve the 'Sustainable Development Goals'. The increasing burden has pushed the manufacturing industry to move towards sustainable production practices for future economic growth. The triple bottom line theory of sustainability shows that economic, environmental, and social sustainability contributes to business success [6], which improves profitability, meets stakeholders' demands, and conserves natural resources [7]. Hence, sustainable manufacturing has become a vital topic, which needs to be addressed by technological innovations, availability of up-to-date manufacturing data, and application of sustainability performance measurement methods [8,9].

Abbreviations: ELCA, environmental life cycle assessment; LCC, life cycle costing; EEA, eco-efficiency assessment; SM, subtractive manufacturing; MQL, minimum quantity lubrication; EBM, electron beam melting; JIT, just in time; DMLS, direct metal laser sintering; FDM, fused deposition modelling; GWP, global warming potential; EP, eutrophication potential; CM, conventional manufacturing; PBF, powder bed forming; LCI, life cycle inventory; SLCA, social life cycle assessment; SLR, systematic literature review; AM, additive manufacturing; UNEP, United nations environment programme; CNC, computer numerical control; SEC, specific energy consumption; LBM, laser beam melting; SLM, selective laser melting; RM, additive remanufacturing; ADP, abiotic depletion potential; AP, acidification potential; CLAD, direct laser additive manufacturing; SLS, selective laser sintering; HPDC, high pressure die casting.

* Corresponding author.
E-mail address: h.wijerath@postgrad.curtin.edu.au (H. Jayawardane).

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Table 1
Keyword selection.

Keyword	Justification
1. Additive manufacturing	This refers to literature on manufacturing processes which achieve the desired shape of the product by addition of raw material.
2. 3D printing	3D printing is a synonym for additive manufacturing.
3. Subtractive manufacturing	This refers to literature on manufacturing processes which achieve the desired shape of the product by removal of raw material.
4. Machining	Machining is a synonym for subtractive manufacturing.
5. Sustainable manufacturing	This refers to literature on manufacturing processes that lowers environmental, economic, and social impacts.
6. Technical feasibility	This refers to literature on feasibility studies of technical properties of material for the intended applications.
7. Life cycle assessment	This refers to literature on environmental impact assessment methods based on a life cycle approach.
8. Life cycle costing	This refers to literature on economic impact assessment methods based on a life cycle approach.
9. Social life cycle assessment	This refers to literature on social impact assessment methods based on a life cycle approach.

Additive manufacturing (AM) is as a resource-efficient manufacturing technology that decreases the material waste through layer by layer deposition of material using 3D model data. [6]. AM is becoming a technology that can support the transition from a linear economy in manufacturing to a circular economy [10]. The inconsistent product quality in polymer AM and higher energy consumption in metal AM have hindered the adoption of the technology. However, recent developments in AM have produced high-quality AM parts with similar functional performance to subtractive manufactured (SM) parts [11,12]. Furthermore, rapid tooling and hybrid manufacturing methods have expanded the applicability of AM in industrial applications [12]. The technological innovations such as AM coupled with sustainability performance assessments could deliver intended sustainable manufacturing targets for industrial applications.

Several sustainability assessment tools and methods have been used in the life cycle approach to evaluate the sustainability performance of AM and SM parts [9]. The environmental life cycle assessment (ELCA), life cycle costing (LCC), and social life cycle assessment (SLCA) are the most prominent tools that assess the triple bottom line objectives. Some studies have integrated ELCA and LCC into tools such as eco-efficiency assessment (EEA) to find environmentally friendly options not entailing excessive costs [6]. However, there are challenges associated with the integrations of technical feasibility aspects into the sustainability performance assessment frameworks for manufacturing. Most sustainability assessment tools and methods assume AM parts have similar technical feasibility as SM parts which does not accurately assess the implications of the technical performance on the sustainability assessment [13].

Although general solutions have been proposed, the tools and methods used in sustainability performance assessments, the comparison of AM and SM in sustainability, and the level of integration of technical feasibility in sustainability performance studies remain unexplored. In this context, this study aims to discover research gaps by reviewing the state of art of technical feasibility assessment methods and sustainability assessment tools used for additive and subtractive manufactured parts. This paper also discusses sustainability performance comparisons as a decision support tool and approaches towards an improved framework for sustainability assessment for manufactured parts.

Method

The paper employs a systematic literature review (SLR) methodology to identify eligible literature and to analyse the gathered information through a structured method. Accordingly, a method has been developed to collect, review, and synthesise articles focusing on the sustainability of additive and subtractive manufacturing utilising available tools and methods.

Selection of articles for review

The structured methodology in SLR was used to define the keywords and the scope of the literature. The aim of the review is to “assess the state of art of technical feasibility assessment methods and sustainability assessment methods used for additive and subtractive manufactured parts”. The following keywords in Table 1 have been derived from the aim of the review.

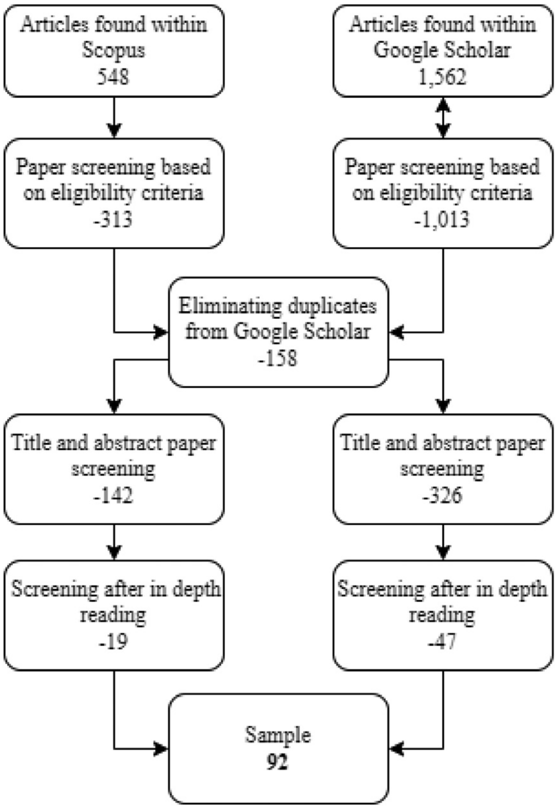

Fig. 1. Paper screening process flowchart [adopted from 15].

The keywords were then structured into a search term by searching all items that contain either keywords by OR logic and searching for all items that contain both keywords by AND logic (“sustainable manufacturing” OR “3D printing” OR “additive manufacturing” OR “machining” OR “subtractive manufacturing”) AND (“technical feasibility” OR “life cycle assessment” OR “life cycle costing” OR “social life cycle assessment”).

The scope of the literature review was defined as the literature available in Scopus [14] and Google Scholar, as they contain very diffused literature on manufacturing. The keywords string was searched within the title, abstract, and keywords of articles in these databases. The article screening process has been presented in Fig. 1. Accordingly, 2,110 research articles were found in Scopus and Google Scholar databases following a structured keyword search method. The following eligibility criteria were used for the initial screening of sources for the literature review and 1,326 articles were removed:

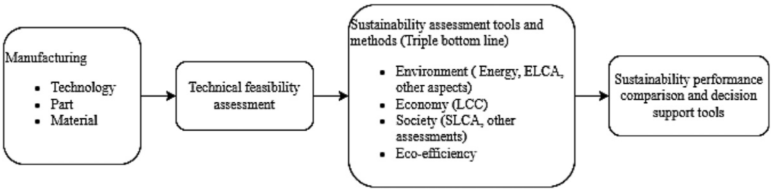

Fig. 2. Theoretical framework of literature review.

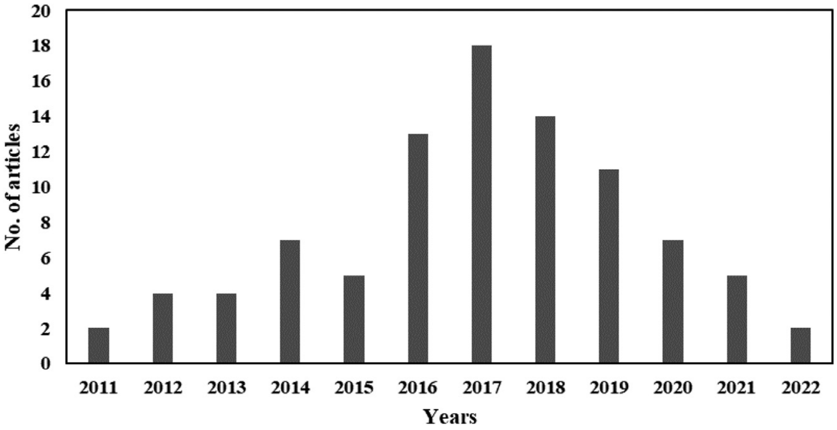

Fig. 3. Number of articles selected for review and their publication years.

- Scientific research published within the last ten years (2011–2022).
- Articles published in peer-reviewed journals and documents published in recognised bodies (e.g., ISO, UNEP).
- Articles published in English, which is an international language.

Out of these articles, 158 duplicate articles were removed. Another 468 articles were removed during the first stage of the screening process based on the relevance of title and abstract to the research question and 66 articles were removed during the second stage of the screening process, which focused solely on new material or process development as they were beyond the scope of the research. The final screening identified 92 sources with relevant themes, which were selected for the literature review.

The results were then categorised into themes and analysed under the theoretical framework as presented in Fig. 2.

Sample and descriptive analysis

Fig. 3 shows the number of articles published in each year from the sample of 92 articles, with 70 articles (76.1%) being published from 2016 onwards. This shows that the interest in sustainable manufacturing has grown significantly in recent years and may be due to the growing activities on combatting climate change. The main publication titles for articles encountered during this review were Journal of Cleaner Production (14 articles), Journal of Industrial Ecology (7 articles), Additive Manufacturing (5 articles), and International Journal of Advanced Manufacturing Technology (5 articles), while other articles were primarily from journals in manufacturing.

Table 2 summarises the literature review carried out in this study by presenting the tools, parameters, and manufacturing techniques evaluated. The table indicates that 51% of articles have used the ELCA framework for environmental assessment, 25% have used the LCC framework for economic assessment, 14% have used SLCA for social impact assessments, and 30% have discussed the technical feasibility of manufactured parts. However, only 2% of the articles have considered the integration of technical, economic, and environmental impact assessments.

The additive manufacturing has been found to offer benefits such as material efficiency, lower supply chain costs, improved functionality of parts, elimination of tools, jigs, and fixtures, and the use of recycled materials over SM. However, lower surface quality, dimensional accuracy, mechanical properties, and microstructure have hindered the applicability of AM in industrial applications compared to SM. The literature was further classified and synthesised in the review to generate meaningful information according to the objectives of the review paper. Furthermore, state of the art for sustainable manufacturing was reviewed, and weaknesses, challenges, and future directions were identified.

Analysis and discussion

Manufacturing involves the process of transforming raw materials into a desired product [11]. The manufacturing process that removes material has been termed as subtractive manufacturing while the manufacturing process that adds material has been termed additive manufacturing, during the development of additive manufacturing technology [16].

Additive manufacturing (AM) technology

Additive manufacturing is an emerging manufacturing technology whereby “material is added layer by layer from 3D model data to obtain the desired shape of the product” [17]. This manufacturing route is a key technology driving the Industry 4.0 and smart manufacturing [8]. Yoon et al. [11] stated that 3D printing is the most predominant additive manufacturing method and has transformed from a rapid prototyping tool to a standard manufacturing technology for end-use products over recent years. Composites, ceramics, metals, biomaterials, and other innovative materials are used to make functional parts in 3D printing [6]. This manufacturing method further eliminates the need for complex fixtures, tools and other cutting fluids [12] whilst allowing customisation, complex freeform fabrication and shorter lead times, hence enabling Just-in-Time (JIT) manufacturing [18]. However, additive manufacturing technology has faced drawbacks such as high machine costs, material costs and energy costs, which have hindered the widespread adoption of the technology [10].

Subtractive manufacturing (SM) technology

Subtractive manufacturing is the process of producing the desired shape and size of the product by removing the excess raw materials with complex tools, fixtures, and jigs [19]. The computer numeric controlled (CNC) machining method enables to achieve the required level of dimensional accuracy and surface properties in modern manufacturing [11]. The material waste and cutting/lubricating fluids used to cool

Table 2
Summary of tools, manufacturing techniques, and sources encountered during the present work.

Tools	Manufacturing Techniques	Author
Technical feasibility assessment (TFA)	Electron beam melting (EBM)	(Aboulkhair et al., 2014, Austin et al., 2017)
	Selective laser melting (SLS)	(Aidibe et al., 2016, Brandl et al., 2012)
	Fused filament fabrication (FFF)	(Bárnik et al., 2019, Brenken et al., 2018, Fernández et al., 2016, Kim et al., 2017, Khalid et al., 2021)
	Powder bed forming (PBF)	(Islam et al., 2013)
	Laser engineered net shaping (LENS)	(Bevan et al., 2017, Abdulrahuman *et al.*, 2018)
	CNC machining	(Boswell et al., 2017)
	CNC machining, laser cladding	(Zhang et al., 2016)
Energy consumption (EC)	SLM	(Huang et al., 2016, Baumers *et al.*, 2017)
	FFF	(Yoon et al., 2014, Ramesh et al., 2022, and Weng et al., 2022)
	LBM, EBM	(Watson and Taminger, 2018)
Environmental life cycle assessment (ELCA)	PBF	(Böckin and Tillman, 2019)
	Directed energy deposition (DED)	(Liu et al., 2018)
	FDM and inkjet printing	(Faludi et al., 2015)
	Laser beam machining (LBM)	(Walachowicz et al., 2017, Landi et al., 2022)
	Selective laser sintering (SLS)	(Kellens et al., 2014)
	Wire additive manufacturing	(Smythe et al., 2020)
	CNC machining	(Halstenberg et al., 2016)
	SLM, CNC machining, forming	(Ingarao et al., 2018)
	Plunge milling, LBM	(Peng et al., 2017)
	SLM, CNC machining	(Peng et al., 2020)
	Laser cladding, CNC machining	(Serres et al., 2011)
Life cycle costing (LCC)	High pressure die cutting (HPDC), direct metal laser sintering (DMLS)	(Atzeni and Salmi, 2012)
	SLM, injection mould tooling	(Huang et al., 2017)
	FFF, SLM, SLS	(Lindemann et al., 2012)
Social life cycle assessment (SLCA)	FFF	(Naghshineh et al., 2020)
	FFF, SLM, SLS	(Matos et al., 2019)
		(Naghshineh et al., 2021, Ruben et al., 2018)
TFA and ELCA	LENS, CNC machining	(Jiang et al., 2019)
ELCA and LCC	EBM, CNC machining	(Paris et al., 2016)
	FFF	(Pereira et al., 2019, Yosofi et al., 2019)
ELCA and design optimisation	Binder jetting, CNC machining	(Tang et al., 2016)
ELCA and eco-efficiency assessment (EEA)	Petrochemical	(Pereira et al., 2018)
ELCA, LCC, and SLCA	CNC machining	(Fatimah et al., 2013)
	FFF, CNC machining	
ELCA, LCC, and Human toxicity potential	FFF	(Ma et al., 2018)
ELCA, LCC, and EEA	EBM	(Mami et al., 2017)
TFA, ELCA, and EC	SLM, CNC machining	(Priarone and Ingarao, 2017)
TFA, ELCA, LCC, and EEA	FFF	(Jayawardane et al., 2021)

cutting tools in the manufacturing process are ultimately disposed of to landfills causing eco-toxicity [20,21]. The CNC machining method for subtractive manufacturing has improved machining performance, minimising waste, and increasing resource efficiency. Furthermore, CNC machining has allowed users to determine the optimum cutting path, reduce machining time through automatic tool changing, development of cutting fluid control to provide minimum quantity lubrication (MQL) and compressed air systems/cryogenic coolant system to improve machined surface properties and tool life [22]. The fabrication of complex geometries from 3D model data in multiple axes has been facilitated by this method. However, the CNC machining method is highly energy-intensive for hard materials and difficult to machine complex geometries [23].

Additive manufacturing vs. subtractive manufacturing

Additive manufacturing (AM) and subtractive manufacturing (SM) are two contrasting manufacturing processes identified in the literature [24]. These processes are distinct from each other, as AM involves adding material to create the desired shape, whereas SM involves removing material from a block to create the desired shape [25]. In practical applications, AM is commonly used for the production of customised, low-volume, complex parts with a lower solid-envelope ratio in sectors such as aerospace, healthcare, and automotive industries [16,19]. In contrast, SM is preferred for the industrial production of large-scale, identical parts with a higher solid-envelope ratio [4].

The unit cost of parts produced by AM remains relatively constant regardless of the scale of production, whereas the unit cost of parts produced by SM decreases significantly with increasing scale of production. This is because SM involves substantial initial costs associated with the acquisition of tools, fixtures, and jigs, which are not required for AM [19].

Part choice in studies of sustainable manufacturing

Additive and subtractive manufacturing processes have advantages and disadvantages over each other in terms of manufacturing an individual part. Selecting a part that could be sustainably manufactured in these processes has been essential in sustainability assessments. Studies have chosen parts to evaluate based on parameters such as complexity [19,23,26], solid-to-cavity/solid-to-envelope ratio [16,25], application [10,13,19], functionality [12], simplicity [11] and availability of standard performance testing criteria [26]. Sustainability assessments have been performed for the parts such as turbine impellers [19,23], pump impellers [26], axisymmetric parts [16,25] and simple mechanical parts [12] based on the parameters as mentioned above. Multi-criteria decision-making models have been widely adopted in these studies to select feasible parts based on the parameters [27].

Material choice in studies of sustainable manufacturing

The material selection for manufacturing is another important consideration in resource efficiency that determines the fundamental properties and the type of manufacturing process, i.e., additive or subtractive [21]. For example, it is unnecessary to use an energy-intensive steel component when a plastic component does the same work with a reasonable lifetime [28]. Raw material production activities resulted in 25% of all anthropogenic CO_2 emissions [29]. Steel, cement, paper, aluminium and aggregate plastics are the major contributors to CO_2 emissions, with steel and aluminium alone being responsible for 28% of CO_2 emissions in material production [25].

Aluminium [25,30], titanium [12,19,23], steel [31] and polymer [11,32,33] have been the preferred materials for further investigation in terms of difficulties associated with material extraction [25] and machining [34], higher strength-weight ratio [19], higher availability of materials in both bulk and powder forms [16], and availability of information on material production/properties [25]. Pusavec et al. [21] have scored the sustainability of materials in terms of abundance of raw material, environmental impact during manufacturing, estimated life, ease of recycling, and cost of the finished product.

It is evident that the sustainability of materials selected for manufacturing has gained prominence in sustainable manufacturing. However, the influence of process parameters during material processing has affected the material composition in AM, which has made it difficult to select a material for AM compared to selecting a material with bulk material properties in conventional SM [16]. Further, high cost of materials, limitations on the range of materials available for production (several metals and composites cannot be controlled by temperature in AM), and limits on the recyclability of materials (plastics and composites have limited recyclability due to degradation of properties) and parts (complex products have parts made from different materials, making it difficult to disintegrate to constituent parts) have hindered the adoption of AM technology [34,35].

Technical performance assessment for sustainable manufacturing

Technical properties of parts were not significantly considered when additive manufacturing technology was only used for prototypes [36]. However, recent applications of AM to produce functional parts used in safety-critical applications, such as aeronautical, medical, and industrial appliances, need to be technically feasible [37,38]. The mechanical properties and technical performance of parts vary with different manufacturing methods, which influences the durability and service life of the appliances. Geometric and dimensional tolerance have been evaluated as primary technical performance indicators in additive manufacturing [39]. However, Mami et al. [13] showed that the technical performance of parts was generally not considered in sustainability performance studies, with the assumption being that parts made by different manufacturing methods possessed the same mechanical performance and service life. Liu et al. [40] stated that the quality and performance of additive manufactured parts might not necessarily be similar to subtractive manufactured parts.

The most common defects of AM parts compared to SM parts have been residual stresses, part deformation due to heat localisation, and oxidation of metallic parts. These defects have been minimised through heat treatment, improvement of the build chambers, novel processing methods, and standardisation of process parameters. The International Organisation of Standardization has a standard for the technical evaluation of additive manufactured parts (ISO 17,296–3) [41] in which part properties should be tested for several technical properties, including surface quality, geometric and dimensional tolerances, mechanical properties (tensile and fatigue strength) and microstructure [42]. Studies have been conducted to improve the additive manufacturing process parameters such as dimensional and geometric tolerance [43], surface quality [44], mechanical properties [36,45] and microstructure [46–48].

Fernández et al. [26] conducted a technical performance comparison of pump impellers made through fused deposition modelling, using standard testing methods for the testing of the hydraulic performance of pumps [49]. It was found that impellers chemically treated with dimethyl ketone have higher hydraulic performance compared to untreated impellers. This shows that improvement of surface quality by post-treatment can increase the functional performance of additive manufactured parts. Studies have also considered technical performance improvement strategies such as weight reduction (composite parts instead of metal parts), design optimisation (topology and shape optimisation) and added functional value (3D printed cooling channels in engine components for higher efficiency) in sustainability assessment studies [4,18,26]. However, these studies did not conduct a comprehensive technical evaluation of parts manufactured by additive manufacturing techniques in order to determine the durability and service life, which could then be integrated into the economic and environmental analysis [19].

Jayawardane et al. [50] considered the technical feasibility assessment of a 3D printed centrifugal pump impeller. The impeller was assessed for dimensional and geometric tolerance, microstructure examination, material property evaluation such as tensile and fatigue tests and hydraulic performance. The technical feasibility assessment results indicated that 100% infill short fibre, carbon-nylon composite material reinforced with fibreglass, was the only candidate material that achieved the benchmark properties of conventional nylon materials. Service life estimation for the pump impeller was made through the fatigue life prediction method. Service life was used as the functional unit for economic and environmental life cycle assessments.

The technical feasibility of AM and SM parts has been tested through mechanical characterisation tests [28], build material property assessments [51], and performance tests. However, due to the variety of process parameters, post-processing (finishing, heat treatment), and materials used in AM, it has been difficult to provide regulation for process parameters and certification of parts for technical feasibility [36]. Further, service life estimation of parts has been used to determine the feasibility in functional applications [50]. In summary, the studies reviewed here show that the technical feasibility assessment of AM parts is imperative for comparative sustainability assessment with SM parts.

Sustainability assessment tools under triple bottom line objectives

Once manufactured parts are found to be technically feasible, they need to fulfil social, economic, and environmental objectives of sustainability. The triple bottom line of sustainability encompasses a given product system's economic, environmental, and social implications [52]. The literature on sustainability assessment of AM and SM parts have been analysed under the triple bottom line objectives in this study.

Environmental assessment of manufacturing

Energy consumption in manufacturing. Several studies have modelled energy consumption in manufacturing for environmental impact assessment using elementary assessment tools [53,54]. Yoon et al. [11] studied the energy consumption of the manufacturing stage of a simple part in conventional formative, subtractive and additive (fused deposition modelling) processes. The specific energy consumption (SEC) method was used for each part in the manufacturing stage, and energy-saving strategies for each process were discussed. It was found that the conventional formative (SEC of 9.9 $kWh.kg^{-1}$) and subtractive manufacturing (SEC of 3.49 $kWh.kg^{-1}$) methods were more energy-efficient when compared to additive manufacturing methods (SEC of 75.1 $kWh.kg^{-1}$) in large scale fabrication, whereas additive manufacturing was viable for small scale fabrication. Furthermore, results showed that conventional bulk forming has the highest efficiency (~100 times that of AM efficiency). However, the study omitted the energy consumption in material sourcing, preparation, tooling, and mould making. It was also stated that the development of technology for additive manufacturing could overcome the barriers associated with mass-scale manufacturing, thereby reducing the SEC by lowering product weight and improving the efficiency of the equipment.

Paris et al. [23] studied the comparative environmental impacts of additive (electron beam melting - EBM) and subtractive manufacturing (CNC machining) methods for aeronautical component manufacturing, mainly considering the energy consumption in the product life cycle. The cumulative energy demand in a life cycle approach was used in the study to measure the environmental impact using ten indicators selected from 'CML 2 baseline 2000′. The results showed that, for a part with a shape complexity factor of 7.08, the EBM additive manufacturing method was found to be more energy efficient (8.3 kWh) compared with CNC machining (27.5kwh). However, when the shape complexity factor (ratio of the volume of material needed in SM to the volume of the part) fell below 2.6 with lower material removal, CNC machining became more energy efficient. This study showed that the shape complexity factor is an important parameter which could affect the energy consumption of manufacturing when selecting a manufacturing method.

Huang et al. [10] studied the energy-saving potential of additive manufactured lightweight aircraft components. Forging, milling, turning, machining, and casting were selected for conventional manufacturing pathways, while selective laser melting (SLM), direct metal laser sintering (DMLS) and EBM were considered additive manufacturing pathways. A life cycle energy modelling approach was used to calculate the energy consumption for each stage of the product life cycle. The modelling was conducted with different estimates for the number of years taken to adopt additive manufacturing for 80% of aircraft components according to three scenarios: slow adoption (28 years), medium adoption (10 years), and rapid adoption (5 years). In the rapid adoption scenario, the results indicated a total primary energy-saving potential of 70–173 million GJ/year by 2050. The majority of the energy and cost savings were found to come from the reduction of weight in aircraft components made by additive manufacturing, which lowered the aircraft fuel consumption.

Wang et al. [55] has evaluated the energy efficiency of AM using a machine learning based multimodal attention fusion network. The results of the numerical experiment showed that machine learning based energy consumption calculation provides accurate prediction compared to conventional energy consumption calculations. Integration of computational models could provide real-time environmental assessment of AM parts.

In summary, the high energy-intensive nature of current metal additive manufacturing methods (material production, manufacturing, and waste) has received global attention to improve the energy-saving potential and minimise resulting emissions through several research studies [56]. The results showed comparatively higher energy efficiencies for AM when applied to custom parts, complex shapes, and critical applications that involve high cost and energy-saving when the design and weight of the components are optimised [57]. Further, energy consumption and other environmental impact assessments could be integrated with machine learning based computational models to improve efficiency and accuracy of assessment.

Environmental life cycle assessment (ELCA) in manufacturing. Several studies identified the environmental life cycle assessment approach as the most influential environmental impact evaluation tool [12,25,33]. In an ELCA, the goal and scope of the study are first established, the inventory of relevant inputs and outputs from a product-system are compiled, and the environmental impacts are ascertained through a product's life cycle to assess, evaluate, and interpret according to the objectives of the study [12,58]. The life cycle impact assessment results are computed either as midpoints or endpoints. Midpoints (global warming potential, cumulative energy demand, abiotic depletion potential, ecotoxicity, *etc.*) are computed directly from the life cycle inventory data, which are relatively difficult to interpret for a general audience [19]. However, endpoints (eco-system quality, resource depletion, and human health) are difficult to compute and entail a degree of uncertainty due to differences in inventory data, coverage of substances in methods, and different characterisation factors in methods [59,60]. However, they are easy to interpret for a general audience [33,61].

Faludi et al. [33] studied two polymer-based standard shape components with holes and features to compare the environmental impact of additive manufacturing (FDM and inkjet) and conventional manufacturing (CNC milling) using an ELCA approach. The ReCiPe endpoint H method was adopted to quantify the environmental impacts for comparison [62]. The utilisation of the build-envelope (maximum physical dimensions of the 3D print area) in AM has reduced idle time-energy and environmental impact per part. On the other hand, CNC machining with maximum utilisation contributes to material waste such as scrap, lubricant, and emissions. These results are essential when correlating machine utilisation with regards to the sustainability impact of the process.

Peng et al. [19] studied titanium alloy impellers for sustainability assessment using the ELCA approach. Plunge milling (CM – Conventional manufacturing), laser cladding forming (AM combined with CM) and additive remanufacturing (RM) were compared in terms of their environmental impact. The study considered replacing conventional machining with additive manufacturing for a repairing process in order to save materials and energy. RM was found to be the most environmentally favourable option followed by AM combined with CM process in terms of global warming potential (GWP), abiotic depletion potential (ADP), eutrophication potential (EP) and acidification potential (AP). Compared to CM and AM, RM reduced GWP, ADP and EP by 64.7%, 66.1%, and 75.4%, respectively. However, AM exhibited a lower environmental impact compared to CM when manufacturing components with complex geometries. CM requires fixtures and tools and may cause possible collisions, invisible zones, and difficulties in cutter access, making it time-consuming and costly for complex parts. However, the use of AM to produce large parts and simple geometries has a higher environmental impact than CM. It should be noted that an assumption made in the reviewed literature was that manufactured products with different methods possessed the same mechanical behaviour. However, this was assumed without conducting any laboratory-based assessments.

Serres et al. [12] studied the environmental impact of a titanium component with different functional and structural features for comparison using the ELCA approach. Direct additive laser manufacturing (CLAD – *Construction Laser Additive Directe* in French) process was compared with CNC milling (CM). The results showed that the CLAD process reduced the environmental impact by 70% compared to the conventional machining process. The environmental impact of additive manufacturing was mainly attributed to the upstream processing (material extraction, material processing and powder production) rather than the actual manufacturing.

Böckin and Tillman [24] conducted an ELCA to manufacture and assemble a light distribution truck. Three midpoint environmental impact indicators, namely, fossil fuel consumption, greenhouse gas emissions and material resource use, were used to quantify the environmental impacts of manufacturing. The comparative assessment considered three scenarios: conventional manufacturing (S0), additive manufacturing (PBF) of engine components (S1) and additive manufacturing of potential components with technology development (S2). The results indicated lower fossil fuel depletion in S1 and S2 and attributed to the energy-intensive nature of 3D printing being offset by use stage savings of fossil fuel. GHG (Green House Gas) emission results showed the lowest figure for the S2 scenario, which was directly linked to a 25% weight reduction due to the optimisation and the selection of alternative materials in AM. The material resource use also exhibited the lowest figure (8.3 kg) in S1 and S2 due to replacing high alloy steel in S0 (11.7 kg) with low alloy steel.

Walachowicz et al. [63] conducted an ELCA on repairing gas turbine burner tips made of nickel-based superalloys, comparing laser beam melting (LBM) additive manufacturing with the conventional manufacturing process. The study focused on variations in recycling rates (0%

to 100%) of metal powder (99% stays in a closed loop) and the quality of recycling (% of contaminants in the recycled feedstock mixture) in order to identify the environmental impacts on material and energy consumption. The results showed that the material consumption (0.004 kg Sb-eq.), energy consumption (1100 MJ) and global warming potential (GWP) (80 kg CO_2-eq.) for conventional manufacturing was significantly higher than that for LBM by 50%, 45% and 88%, respectively, for the 80% recycling rate scenario. This indicated that the LBM method possessed a lower environmental footprint compared to conventional manufacturing for the same recycling scenario.

Peng et al. [64] conducted a similar ELCA study for the comparison between additive and subtractive manufacturing processes of an aircraft valve body using ReCiPe midpoint H (18 indicators) and endpoint (3 indicators) indicator methods. The study showed that the environmental footprint of the additive manufactured part was 37.42% lower than that of the subtractive manufactured part. Kafara et al. [65] compared the environmental impacts of mould cores manufactured by additive manufacturing and conventional mould manufacturing. This showed that the AM significantly lowered the environmental impacts of mould manufacturing.

Overall, the articles mentioned in this section have followed the structured guidelines of an ELCA and have highlighted the potential of AM in a sustainable manufacturing landscape. Parameters including the scale of production, technology adoption scenarios and use of recycled feedstock have been evaluated to portray a snapshot of the sustainability potential of additive manufacturing. The scope of the ELCA should cover the complete cradle-grave analysis to cover all the environmental impacts of a product. Further, the life cycle inventory (LCI) used in the studies have reported limited inputs and outputs in terms of comprehensive energy consumption, material consumption, and process emissions due to non-disclosure of information by material and equipment manufacturers, which results in studies relying heavily on assumptions. This could be solved by using commercial LCA software like SimaPro in the assessments.

Other aspects of environmental impact in manufacturing. Material consumption, design optimisation and process emissions are other aspects that have been studied to determine the environmental impacts of manufacturing [13,18]. Kellens et al. [32] studied the environmental impact of the selective laser sintering (SLS) additive manufacturing method using a parametric model. The model included a time study (productive time – laser sintering and recoating; non-productive time – machine tool cleaning, preparation, and heating), a power study (standby, pre-heating, exposure, and reheating) and a consumables study (compressed air and powder material) to develop models separately for the environmental process, impact, and improvement potential. The impact model for AM showed a total environmental impact of 35.56 eco-points that was ascribed equally between waste materials (50%) and energy consumption (50%). The improvement potential model indicated the potential to improve nesting efficiency (increased utilisation of build-envelope) by stacking the build-envelope, optimising machine tool control to reduce non-productive time and using recycled feedstock to reduce environmental impact.

Tang et al. [18] developed a framework to evaluate the environmental impact of manufacturing an engine bracket through the binder jetting additive manufacturing process. The environmental impact assessed by ELCA was improved by changing the product design through shape and topology optimisation for additive manufacturing. The results indicated a GWP of 49.3 kg CO_2-eq for the design optimised additive manufactured part compared to 55.83 kg CO2-eq for the CNC machined part and attributed to lower material and energy consumption given the optimised part design. This result confirms that additive manufacturing can offer lower environmental impacts compared to CNC machining when design optimisation is considered.

Pusavec et al. [21] evaluated conventional and unconventional subtractive manufacturing methods for their sustainability performance. Unconventional methods like high pressure jet assisted machining and cryogenic machining have significantly lowered the environmental burden of conventional subtractive manufacturing. This shows that innovation in manufacturing technologies within the same dimension of subtractive manufacturing could lower the environmental impacts of manufacturing.

Material consumption in additive and subtractive manufacturing has been extensively researched in order to reduce the environmental implications of material extraction. Cruz Sanchez et al. [66] studied the potential use of recycled plastic composites as feedstock in additive manufacturing. The main challenges for recycled plastics have been structural and morphological issues, the feasibility of production and stability of polymers and the presence of low molecular weight compounds such as additives. Metal recycling has also been investigated by Smythe et al. [67] for the recycling of titanium powder since the material cost for titanium is increasing significantly whilst the availability of ores is rapidly depleting. The main barriers to the use of recycled titanium feedstock have been the embrittlement of interstitial elements and a high chance of contamination.

Since environmental impacts play an increasingly significant role in sustainability assessments, research on environmental impacts has proliferated. Energy consumption modelling, environmental life cycle assessments with different indicators and indicator types and other frameworks have been used to assess the environmental impacts of additive and subtractive manufactured parts. Hotspots in environmental impact have been identified as part weight, lower build volume utilisation, lower machine utilisation, material waste, energy mix and high energy consumption, with these issues being tackled through design optimisation, build volume optimisation, recycled material feedstock, the use of clean energy and efficient machines.

Economic assessment of manufacturing

The value-addition to the global economy through advanced manufacturing methods continues to increase [68]. The applications of additive manufacturing have been emerging in high value, low volume, customised markets such as medical equipment and tools manufacturing, aircraft and space applications, customised sports applications, and consumer goods manufacturing [8,69]. In this context, there is a growing interest to quantify the economic implications of these product systems [70]. Economic assessments have been predominantly conducted through the life cycle costing (LCC) approach before introducing a structured ELCA framework [71]. The LCC includes the costs from the cradle to the grave, in all stages of the product life cycle (i.e., material extraction, material production, manufacturing, use and end-of-life), which are evaluated using the same LCI used in the ELCA [6] in order to meet conformity of comparison. Developments in additive manufacturing technology have offered economic benefits such as production flexibility, reduced machine/material costs and material/energy wastage.

Furthermore, the capital investment costs of additive manufacturing (3D printer capital costs range from US$5000~1000,000) have been offset by cheaper operating costs (15% reduction in AM part unit cost compared to conventionally manufactured part) over the lifetime of the 3D printer [69]. Cost savings have also been explored in AM part integration, which has the potential to reduce costs by 80% through the elimination of assembly and logistic costs for each part [72]. The cost of subtractive manufacturing has been reduced through cheaper machines, lower maintenance costs, MQLs, and higher tool life [73].

Huang et al. [71] studied the economic implications of additive manufacturing (SLM) and conventional manufacturing (CNC machining) injection moulding tools. The lead-time analysis shows that on-site AM has a 12% lower lead time compared to conventional offshore manufacturing. However, on-site AM is four days slower than conventional onshore manufacturing due to longer production times. These higher lead times translate into plant downtime and result in increased costs. A 15% to 35% cost saving was noted in distributed additive manufacturing scenarios over conventional manufacturing methods for a functional unit of 1 million injection moulding cycles, i.e., the lifetime of the injection mould in a number of injection moulding cycles, in the LCC. Furthermore, this study evaluated GHG, along with life cycle costs, in order to help interpret the environmental implications of economic decisions (Huang et al., 2017).

Atzeni and Salmi [74] evaluated the economic impacts of an additive manufactured aircraft landing gear. The life cycle costs of the manufactured parts by high pressure die casting (HPDC) and DMLS were compared in the study. The results showed that unit cost depended strongly on the batch size due to the high cost of the die used to cast the landing gear ($210 for die cost per unit in a batch of 100 landing gears – 91% of the total cost). The total cost of the landing gear through the DMLS method was $526 (machine cost per unit was $473 – 90% of the total cost). The break-even point for the HPDC and DMLS methods was 42 units. This result suggested that a future reduction in machine costs could increase the break-even point between conventional manufacturing methods, thereby making AM cost-competitive in the future.

Lindemann et al. [72] developed a time-driven activity-based cost model for their life cycle cost calculation. The cost calculation for a stainless steel 316 L aerospace bracket resulted in a cost portfolio of 73% machine costs and 12% material costs for a batch size of 190 parts. Labour costs were only calculated for loading and unloading since AM is regarded to be a blind production process (without the involvement of labour).

The reviewed studies in this section have shown that cost is an important consideration in manufacturing business decision making. The results show that the costs of AM methods have been higher than their conventional manufacturing counterparts, mainly due to high machine costs (capital/purchase costs and operational costs), which are expected to be reduced due to further developments in technology and the expiration of intellectual property rights in the additive manufacturing area. Furthermore, additive manufacturing supply chains in distributed networks have the potential to offset higher lead times for parts manufactured offshore. Studies have considered life cycle costs along with environmental impacts for better visualisation of triple bottom line objectives.

Social implications of manufacturing

The social sustainability perspective of additive and subtractive manufacturing has not been researched extensively [6]. However, the social implications of manufacturing have been studied for both qualitative and quantitative impacts through different assessment methods. For example, Ma et al. [6] stated that the social life cycle assessment (SLCA) by UNEP/SETAC [75] is the most commonly used framework for social impact assessment. The social impact indicators have been modelled through stakeholder categories of the local community, society, consumers and value-chain actors [75]. Although the Global Reporting Initiative [76] has introduced 19 social impact indicators categorised as core and additional indicators, most are qualitative indicators, resulting in quantification difficulties.

Health and safety have been quantified in terms of human toxicity potential (HTP) in several social impact assessments due to the quantitative nature of this parameter. The results have found that HTP is positively correlated with the weight of the material used in the manufacturing process. Tang et al. [18] compared the social impacts of the HTP of the binder jetting process (AM) with SM and found that higher amounts of dichlorobenzene equivalent (DCB-eq.) in both manufacturing processes lead to higher human toxicity potential, thereby exposing a negative social impact of manufacturing. The results indicated that an AM part produced 44.1 kg of DCB-eq., whereas an SM part only produced 29.5 kg DCB-eq. This highlights that additive manufacturing may exhibit more negative social implications due to higher HTP impacts.

Matos et al. [77] investigated the social impacts of additive manufacturing using an SLCA method. Social impact indicators of health and social well-being, institutional, legal, political, equitable, quality of the living environment and economic and material well-being were selected for assessment. The results showed that AM possesses better social performance, such as a reduction of occupational hazards, recognition of professional status, new opportunities for leisure and recreation and personalised products improving satisfaction. However, exposure to harmful substances was identified as a negative social impact of additive manufacturing.

Naghshineh et al. [78] developed an SLCA framework based on the UNEP/SETAC [75] framework in order to quantify the social impacts of additively manufactured products. This framework proposed several subcategories of social impact indicators, stakeholder categories and life cycle stages. The qualitative survey enabled the gathering of respondents' perceptions to determine social impact indicators, which were later converted to a single social impact score. A UK 3D printing company case study was used to validate the selection of social impact indicators proposed in the developed framework. Naghshineh et al. [79] further evaluated the social impacts of additive manufacturing in a stakeholder-driven framework. The study concluded that 29% of indicators were assigned to the local community, 25% were assigned to consumers, 25% were assigned to society, 14% were assigned to value chain actors, and 7% were assigned to employees, reflecting the degree of AM impact for each stakeholder category.

Ruben et al. [80] developed a simplified two-level generic SLCA framework from the UNEP/SETAC [75] framework, including first-level enablers and second-level indicators. The first level includes stakeholders such as employees, products, and society. The second level includes three indicators under employees (fair salary, working hours, and local employment), products (product safety, orientation, and secure operating conditions), and society (technology development, contribution to economic development, and operational commitment to sustainability issues). The framework was validated by a case study of an Indian automotive manufacturer, which identified two social hotspots, including contribution of manufacturing to economic development and the operational commitment to sustainable issues towards the societal stakeholders.

Bours et al. [81] analysed the hazardous implications of additive manufacturing to human health and developed a framework to minimise hazards and social impacts. The study identifies the sources of emissions of particulate matter, the toxicity of materials (feedstock, solvent, washing compounds), explosion, and fire as potential negative social impacts. Establishing a hazard management framework in an AM system similar to SM systems could lower the negative social impacts.

Social impact assessments in additive and subtractive manufacturing are limited, unlike ELCA and LCC assessments, due to the inherently qualitative nature and the uncertainty of indicators subjected to bias [6]. However, the social life cycle assessment framework proposed by UNEP/SETAC [75] has garnered the interest of several researchers in order to develop a framework and conduct empirical research in this domain. It was found that several AM methods have better positive social impacts (occupational hazards, job satisfaction and opportunities for leisure and recreation) on the local community, stakeholders, consumers, and overall society compared to conventional manufacturing. However, HTP was identified as a major negative social impact of AM.

Eco-efficiency analysis

It is challenging to objectively assess the best options that are simultaneously economically and environmentally feasible, as an environmentally friendly option may not be cost-competitive whilst a cheaper option may not offer the required level of environmental benefit [82]. A substantial amount of research has been carried out to assess the environmental and economic sustainability of manufacturing separately. However, studies have not considered the optimisation of technical, economic, environmental and social implications in order to simultaneously meet those four objectives [8]. Therefore, eco-efficiency analysis (EEA) is an important tool to address this sustainability balance as it integrates the life cycle costs and environmental impact into a single indicator to analyse the environmental impact made per dollar invested in a product.

The eco-efficiency analysis aims to determine cost-competitive and environmentally friendly products made through different manufacturing techniques. The framework uses a distance to target approach, making it suitable for comparative analysis rather than a definitive study. A micro-level improvement in the product or process could be guided to a macro level target through this study [83]. The EEA tool has been used to assess environmental and economic impacts together in order to simplify the interpretation of the sustainability performance of power supply systems [84], aircraft applications [13], nanocellulose [85] and petrochemical production [86].

Mami et al. [13] evaluated the sustainability of 3D printing in the aeronautical industry using the eco-efficiency approach, with ELCA being aggregated with LCC in order to identify eco-efficiency strategies. A case study was conducted for an aircraft doorstep to compare the eco-efficiency of additive manufacturing and conventional manufacturing. Three scenarios, namely, conventional manufacturing, additive manufacturing, and additive manufacturing with topology optimisation, were selected for comparison. The results were analysed through a normalisation procedure interpreted as an X-Y scatter diagram, which showed that additive manufacturing possessed benefits over conventional manufacturing in terms of cost and environmental impact.

Jayawardane et al. [50] evaluated the techno-eco-efficiency performance of a 3D printed centrifugal pump impeller using a life cycle approach. Both ELCA and LCC were conducted using the same LCI generated from manufacturing and other secondary data. The results of ELCA and LCC were normalised to have common denominators for comparison purposes and to reduce complexity. The results were integrated into the EEA, which concluded the most eco-efficient option to be a 3D printed impeller made from 100% infill carbon-nylon composite material reinforced with fibreglass.

The EEA has been used to integrate the results of the ELCA and LCC for a decision-making. The eco-inefficient options found in the eco-efficiency portfolio could be further improved by incorporating cause diagnosis and improvement strategies. This is an iterative process that continues until the eco-efficiency of a product can be achieved or else can no longer be improved. This improved techno-eco-efficiency assessment tool combines technical feasibility assessment with environmental and economic assessments to assess the triple bottom line objectives.

Sustainability performance comparisons of AM and SM parts

Comparative assessment of manufacturing technologies to determine the feasibility of manufacturing a part is an important aspect of modern manufacturing [87]. A sustainable manufacturing system should meet all the aspects of the triple bottom line objectives of sustainability as well as the technical aspects [20]. Several studies have proposed frameworks for the selection of technically feasible and sustainable processes to manufacture parts.

Watson and Taminger [16] used a resource consumption-based computational model for sustainability performance measurement as a decision support tool. The model stated a critical volume fraction value, defined by resource consumption. Additive and subtractive methods were found to be equally efficient in manufacturing a product through this framework. Lower volume fractions would indicate additive manufacturing methods to be more suitable than subtractive manufacturing methods and vice versa.

Bikas et al. [88] also formulated a decision support tool for additive manufacturing based on a probability score (0 to 1) assignment for unfeasible, unlikely, likely, very likely, and feasible outcomes in a multi-criteria logical flowchart. This framework considered criteria in the first level (presence of complex internal structures, freeform surfaces, controlled porosity, and integration of multiple parts), second level (machine constraints, material constraints, process constraints, and part constraints), and third level (manufacturability and post-processing by a single process or hybrid processes). The framework identified that AM is not suitable for parts with unexposed features making it unable to remove residual material and support structures. Further, hybrid manufacturing methods could be utilised for applications that require specific tolerances that could be completed by post-processing with SM methods.

Several studies have formulated decision support tools by incorporating parameters such as batch size for process selection [89] and solid to cavity ratio [25] when comparing the environmental impact and energy-saving potential of parts manufactured from aluminium alloys by conventional forming, subtractive manufacturing, and additive manufacturing processes. Priarone and Ingarao [4] utilised life cycle emissions for sustainability performance comparison between 3D printed and CNC machined parts. The batch size or scale of production was considered to select the manufacturing method with the lowest life cycle emissions. Comparative assessments have shown positive environmental implications for additive manufacturing due to improved resource efficiency and lower emissions [69].

Yosofi et al. [27] also developed a framework to measure the triple bottom line sustainability performance of additive manufacturing methods through a graphical visualising tool (radar chart) with a ‘distance to target’ approach. The parameters included electrical energy consumption, mass of part, mass of support, cost, and surface roughness. The results showed that parts manufactured with material jetting AM (3D inkjet process cured by UV light) exhibited the lowest environmental impact and life cycle costs compared to conventional SM parts. The graphical model proposed by Yosofi et al. [27] have integrated the technical performance of the AM process by linking the surface roughness performance of the AM part with the environmental and economic impact assessment, which is a step towards integrating technical feasibility into sustainability performance. However, this study considered a limited number of indicators compared to other researchers for sustainability assessments [90,91].

Life cycle sustainability assessment (LCSA) aims to assess environmental, economic, and social aspects of manufactured parts through ELCA, LCC, and SLCA tools [6]. However, the assessment is limited to individual aspects and requires integrative approach to determine environmental impacts per dollar invested in a product.

The ‘techno-eco-efficiency framework’ proposed by Jayawardane et al. [50] manages to integrate technical, economic and environmental impacts into a single framework to evaluate sustainability performance of AM and SM parts. The application of the decision support framework has found that AM parts significantly lower the environmental impacts compared to conventional SM parts. Further, AM parts were found to be eco-efficient since the impact of higher costs in AM have been offset by the lower environmental impacts.

In summary, the decision support tools developed by several researchers have considered a primary analysis of the break-even points of energy consumption and life cycle costs. In contrast, some studies have used technical characterisations such as shape complexity, volume fraction/solid-cavity ratio, and batch size parameters for process selection. There exists a need for comprehensive decision support tools that could integrated life cycle costing, life cycle environmental impact, and technical aspects of the parts to select optimum methods for sustainable manufacturing assessment and decision making.

Lessons learned and research gaps

Additive manufacturing has revolutionised sustainable manufacturing, evolving from rapid prototyping technology to a manufacturing-scale industry. The following lessons were learned, and respective research gaps were identified from the literature review.

Applicability of AM

Some studies have evaluated the technical properties of manufactured parts and have improved process parameters to produce technically feasible additive manufactured parts. The studies have carefully considered the design, material, and process for manufacturing a part for technical feasibility assessments. The technical feasibility has been assessed under mechanical characterisation, build material properties, and functional performance. AM parts are required to have comparable technical feasibility to SM parts for sustainability performance comparisons in real world applications.

Integration of technical feasibility to sustainable manufacturing

The technical aspects (reliability, durability, and service life) of additive manufactured parts have been widely disregarded in sustainability assessments, thereby implicitly assuming similar technical performance as the conventional subtractive manufactured counterparts. Consideration of the same durability of these parts could either underestimate or overestimate the sustainability performance of products [90]. The integration of the technical performance into sustainability performance assessment tools could result in realistic outcomes.

Integration of sustainability assessment methods

The triple bottom line objectives of environmental, economic, and social impacts have been extensively assessed in several literature individually. However, the integration of these objectives has not been adequately applied or researched. Eco-efficiency analysis has received recent attention by several authors, given that the environmental implications using ELCA and economic implications using LCC can be integrated into a single indicator to find the most eco-efficient option(s), followed by a social impact assessment of the eco-efficient options. In addition, the ability to incorporate improvement strategies and the use of 'distance to target' approaches have made it suitable for comparative assessment.

Lack of consideration of social aspects

The social impacts of AM parts have not been adequately investigated, except for a few notable studies which have evaluated social impacts through an SLCA framework. This could have been predominantly due to the qualitative nature of several social impact indicators and the complexities with the integration of social aspects into the technical assessments.

Material recycling

Furthermore, when comparing the sustainability performance of AM and SM parts, the distinction of system boundary and the scope of the ELCA and LCC affects the accuracy of the results. Since some studies have not included the material processing stage or end-of-life stage in the scope of the life cycle assessment, an accurate comparison can only be made considering all the input and output processes of all life cycle stages. The resource consumption in feedstock and waste associated with the disposal of end-of-life products regarding product life cycle approaches has a significant bearing on the triple bottom line objectives of the sustainability performance of manufactured parts. Few studies have researched the sustainability performance assessment of 3D printed parts made of recycled feedstock using circular economy principles. However, limited research on the technical investigation of parts made from recycled feedstock using different technologies has left much of this research area unexplored.

Conclusion

In conclusion, the unsustainable manufacturing processes have resulted in socio-economic and environmental consequences that need to be addressed through a structured theoretical framework. This review presents a systematic review of the state-of-the-art of frameworks and methodologies used in the sustainability performance assessment of additively and subtractive manufactured parts to identify barriers and propose improvement strategies.

The studies that could further contribute to the current body of knowledge in sustainable AM include, the investigation into the tools and methods used in triple bottom line sustainability performance assessments, the comparative analysis of sustainability performance between additive and subtractive manufacturing, the extent of integration of technical feasibility of sustainability performance studies, and to explore the right material recycling strategies to further improve sustainability of manufacturing.

The following findings emerged from this review in line with the themes addressed and several managerial insights has been identified.

- Manufacturing a product requires careful consideration in the aspects of design, material, and process which affects the technical, economic, environmental, and social impacts. The technical feasibility of AM and SM parts could be assessed through mechanical characterisation, build material properties, and the performance of the selected part in the functional application.
- It is imperative to incorporate the technical feasibility into sustainable assessment to obtain an accurate comparison of AM and SM parts as estimated service life could significantly affect the life cycle results.
- The sustainability performance assessment methods need to be deployed to provide a holistic overview of the trade-off between the economic and environmental performance of a manufactured part. Eco-efficiency assessment (EEA) could be used as an integrative approach to assess economic and environmental impacts combinedly. Material consumption, design optimisation, and process development should be considered in environmental impact assessment studies.
- The social impacts of AM and SM parts need to be assessed through social life cycle assessment (SLCA) and human toxicity potential (HTP) assessment methods.
- Material processing and end-of-life processing stages of the product life cycle could be improved by considering circular economy strategies such as the use of recycled polymer and metal composites as feedstock to enhance the sustainability outcomes of additive manufacturing strategies.

The results could also assist in achieving United Nations sustainable development goals (SDG) such as pollution prevention (SDG 6), cleaner production (SDG 7), simplified supply chains (SDG 9), sustainable sourcing (SDG 12), and product performance (SDG 13) [34].This study highlighted the existing research gaps in sustainable AM and SM, proposed solutions for future work in sustainable AM which could assist researchers and industry to develop tools, frameworks, policies, and technology to improve the sustainability of manufacturing.

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Ethics approval

The ethics approval for this research work was obtained from Curtin University under approval number HRE2020–0203.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The research data and material will be made available at Curtin Research Data Collection.

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APPENDIX B – ARTICLE 2

Jayawardane, H., I. Davies, G. Leadbeater, M. John, and W. Biswas. (2021). ‘Techno-eco-efficiency’ Performance of 3D Printed Impellers: An Application of Life Cycle Assessment. *International Journal of Sustainable Manufacturing. 5 (1): 44-80.* DOI: 10.1504/IJSM.2021.116871.

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Authorship agreement

I, Heshan Thenuka Wijerathne Jayawardane, contributed 80% to the paper entitled ‘Techno-eco-efficiency' performance of 3D printed impellers: an application of life cycle assessment’.

Mr. H.T.W. Jayawardane

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Author	Signature
Ian J. Davies	
Garry Leadbeater	
Michele John	
Wahidul K. Biswas	

'Techno-eco-efficiency' performance of 3D printed impellers: an application of life cycle assessment

Heshan Jayawardane, Ian J. Davies,
Garry Leadbeater, Michele John and
Wahidul K. Biswas*

School of Civil and Mechanical Engineering,
Curtin University,
Bentley, WA 6845, Australia
Email: h.wijerath@postgrad.curtin.edu.au
Email: i.davies@curtin.edu.au
Email: G.Leadbeater@exchange.curtin.edu.au
Email: M.Rosano@curtin.edu.au
Email: W.Biswas@curtin.edu.au
*Corresponding author

Abstract: Rapid industrialisation had led to a scarcity of resources. The concept of sustainable manufacturing has emerged to address this scarcity and to minimise environmental degradation. 3D printing also known as additive manufacturing, could potentially reduce material wastage, energy consumption and resulting emissions. A 'techno-eco-efficiency' framework was developed to produce technically, economically, and environmentally feasible centrifugal pump impellers 3D printed using the fused filament fabrication process. Firstly, surface properties, geometric properties, build material properties, static structural and dynamic properties, and the hydraulic performance of impellers were assessed in order to investigate how process parameters, such as infill pattern, infill rate and reinforcement material affect the technical performance. Secondly, the eco-efficiency performance of technically suitable impellers was assessed using environmental life cycle assessment, life cycle costing tools and portfolio analysis. Thus, this 'techno-eco-efficiency' framework was used to achieve sustainable manufacturing and could act as a decision support tool for selecting cost-competitive, environmentally benign, and technically feasible products. Alternatively, it would assist product designers and manufacturers to minimise a trade-off between technical and resulting eco-efficiency performance.

Keywords: additive manufacturing; eco-efficiency; life cycle assessment; 3D printing; sustainable manufacturing; sustainability assessment; fused filament fabrication; FFF; composite additive manufacturing.

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Biographical notes: Heshan Jayawardane is a PhD student at the Sustainable Engineering Group at Curtin University. He has obtained his BSc (Eng) in Mechanical Engineering from University of Moratuwa, Sri Lanka. He is currently working on a research project entitled, 'Eco-efficiency performance

comparison of additive and subtractive manufactured parts'. His research interests include composite additive manufacturing, metal additive manufacturing, recycled-plastic additive manufacturing, life cycle assessment, remanufacturing and finite element analysis.

Ian J. Davies is an Associate Professor at the Department of Mechanical Engineering, Curtin University. He has obtained his PhD in Materials Science from the Imperial College, London. He is also a Visiting Professor at the Tokyo University of Agriculture and Technology. His research interest includes polymer matrix composites, 'green' composites, ceramic matrix composites, biomaterials, modelling of human tissue, structural ceramics, bioceramics and modelling failure in brittle materials.

Garry Leadbeater is an Adjunct Senior Lecturer at the Department of Mechanical Engineering, Curtin University. He graduated from the Nottingham University, UK, in 1978, in Metallurgy and Materials Science and subsequently received his PhD at the same university in the field of Fatigue and Tribology related to Aerospace Alloys. His research interest includes advanced materials and materials production processes.

Michele John is the Director of the Sustainable Engineering Group, Curtin University. She has obtained her PhD in Resource Economics from the University of Western Australia. Her research interests include life cycle assessment, waste management, sustainability metrics and sustainability education. She has worked internationally in the mining industry in a number of senior executive positions, and as an academic in Australia.

Wahidul K. Biswas is an Associate Professor at the Sustainable Engineering Group, Curtin University. He has obtained his PhD in Sustainable Futures from the University of Technology, Sydney. He teaches and coordinates a core undergraduate engineering unit, Engineering for Sustainable Development. He has carried out extensive life cycle assessment research for the Australian agricultural, alternative fuels, building and construction, manufacturing, mining, gas and water sectors.

1 Introduction

3D printing, also known as *additive manufacturing*, is an emerging manufacturing technology whereby material is added layer by layer from 3D model data to obtain the desired shape of the product (International Organization for Standardization, 2015b). 3D printing has transformed from a rapid prototyping tool to a manufacturing technology for end-use-products over recent years (Yoon et al., 2014). Functional products with high value can be 3D printed using composites, ceramics, metals, biomaterials, and other innovative materials. 3D printing eliminates the need for complex fixtures, tools and other cutting fluids (Morrow et al., 2007; Serres et al., 2011) whilst allowing customisation, complex freeform fabrication, and shorter lead time, hence enabling just-in-time manufacturing (Tang et al., 2016). Extensive research has been conducted to develop 3D printing technology in order to reduce current drawbacks such as machine costs, material costs, and energy costs (Huang et al., 2016) and to improve process parameters which create parts with better dimensional and geometric tolerances (Brenken et al., 2018), surface quality (Aboulkhair et al., 2014), mechanical properties (Kim et al.,

2017) and microstructure (Aidibe et al., 2016). The Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2016) believes that 3D printing could be one of the five key technologies disrupting and advancing the Australian manufacturing industry through transformation into a highly integrated, collaborative, and export-focused ecosystem that provides high-value customised solutions within global value chains.

Regardless of the extensive innovation, the current manufacturing industry is responsible for 35% of global energy usage as well as 20% of global CO_2 emissions (Priarone and Ingarao, 2017). The resource demand for manufacturing has also increased material extraction, which accounts for 10% of Australian total energy usage (Australian Renewable Energy Policy, 2017). Accelerated levels of manufacturing have not only generated higher values of products but also increased adverse impacts on the environment and society (Peng et al., 2018). The exhaustive nature of resource consumption needs to be dematerialised through innovative sustainable manufacturing strategies such as 3D printing.

Quality and technical performance of functional parts depend on material properties and manufacturing methods (Bárnik et al., 2019b). However, the technical performance of 3D printed parts had not been considered in sustainability performance studies, assuming that the parts made by different manufacturing methods possess the same properties and same service life (SL) (Peng et al., 2017; Mami et al., 2017; Liu et al., 2018; Ingarao et al., 2018). Technical evaluation of 3D printed parts has been standardised by ISO 17296-3 (International Organization for Standardization, 2014) in which part properties have been considered in terms of surface roughness, dimensional tolerance, tensile properties, hardness, fatigue properties, and build material properties (density, porosity and microstructure) (International Organization for Standardization, 2015a). Few studies have been conducted on technical feasibility assessments of 3D printed parts using standard testing methods for functional applications (Zhang et al., 2018; Fernández et al., 2016) whilst weight reduction and design optimisation have been considered as technical aspects in relatively few sustainability assessments (Priarone and Ingarao, 2017; Tang et al., 2016; Fernández et al., 2016). However, these research projects did not integrate the technical performance of products with sustainability assessment, which this paper has presented in order to ensure the technical suitability of sustainable 3D printed products.

The mechanical performance of products, especially durability has a significant bearing on their service lives, economic and environmental sustainability performance (Peng et al., 2017). Holistic models considering life cycle management tools have been preferred to conventional models in order to validate the investments in sustainable technologies (Ma et al., 2018). The environmental impacts of 3D printing have been predominantly assessed through an environmental life cycle assessment (ELCA) approach (Peng et al., 2017; Ingarao et al., 2018; Saade et al., 2020; Böckin and Tillman, 2019), which has been identified as the most effective environmental impact evaluation tool. Economic impacts of 3D printed parts have been evaluated using the life cycle costing (LCC) approach where the cost associated with all stages of the product life cycle, i.e., design, manufacture, use and end-of-life. Associated costs have been evaluated using the same life cycle inventory (LCI) developed for the ELCA (Ma et al., 2018; Mami et al., 2017) in order to maintain conformity for comparison. An eco-efficiency (EE) analysis assumes that economic and environmental impacts should be considered together in order to select cost-competitive and environmentally benign options (Kicherer et al., 2006) which can be used to assess the economic and environmental sustainability of technically feasible parts.

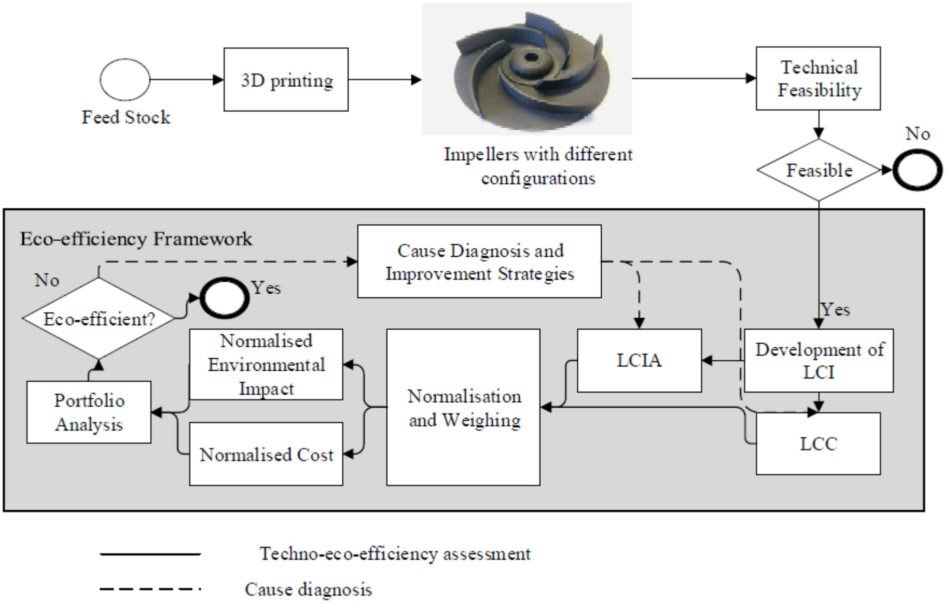
This study aims to investigate the influence of technical performance on economic and environmental parameters and develop a framework to achieve sustainable manufacturing while serving as a decision support tool. Firstly, the paper presents the technical feasibility assessment of 3D printed specimens and parts. Following this, the paper presents a combination of ELCA and LCC for the EE analysis. Finally, technically feasible eco-efficient 3D printed parts are obtained through this 'techno-eco-efficiency (TEE)' framework.

2 Methodology

2.1 Description of the framework

A new methodology for evaluating the technical, economic, and environmental performance of 3D printed parts was required to determine the sustainability of 3D printing as a manufacturing strategy. A 'TEE' framework was thus developed by combining a technical feasibility study with an EE assessment. The EE of technically suitable 3D printed products was assessed following Arceo et al. (2019). The purpose of the framework was to select 3D printed products that could potentially offer the required level of technical performance in an economic and environmentally friendly manner.

Figure 1 Theoretical framework (see online version for colours)



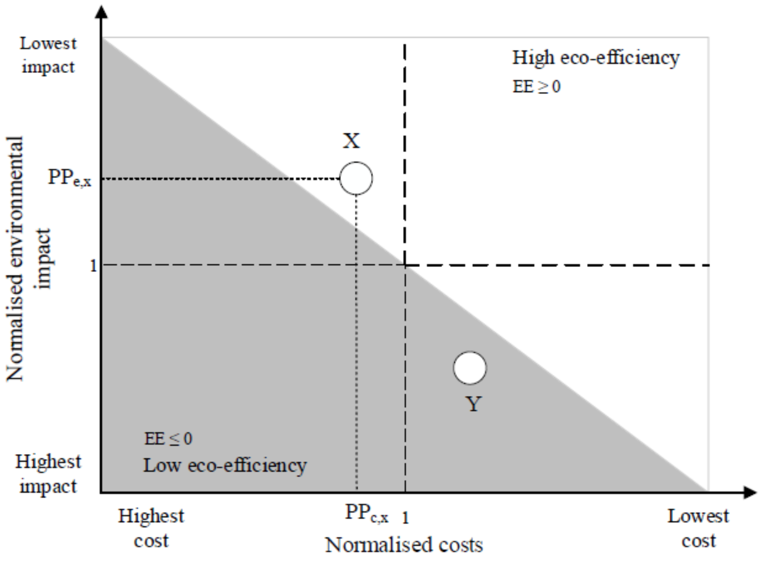
Firstly, the feedstock material was added layer by layer by the 3D printer according to the 3D model data to form the desired geometry of the part in different configurations (Figure 1). Secondly, 3D printed parts with different configurations were evaluated for technical feasibility by benchmarking the technical properties of the parts against those of similar parts made of bulk material in conventional subtractive manufacturing, e.g., computer numerically controlled (CNC) machining.

Thirdly, the EE performance of technically feasible 3D printed parts was assessed in order to ascertain whether parts could be manufactured with reduced environmental impact whilst not entailing excessive cost. The first step of the EE framework was to apply ELCA and LCC to determine environmental impacts and life cycle costs of these 3D parts. In order to perform these two analyses, LCI for each technically feasible part had to be developed by quantifying relevant inputs and outputs from all life cycle stages of the product. The inputs and outputs of the LCI were entered into the ELCA software in order to determine the relevant life cycle environmental impacts (LCEI). The unit cost values of inputs in the LCI were used to estimate LCC.

The EE framework combines the LCC assessment with the ELCA to create an EE portfolio for each product. In order to combine LCEI and LCC, they should be first normalised such that both parameters have common denominators, which ensures comparability and reduces complexity (Kicherer et al., 2006). The EI values were normalised by dividing with the gross domestic environmental impact (GDEI/Inh) per inhabitant whereas LCC was normalised by dividing with the gross domestic product (GDP) per inhabitant.

The EE portfolio (Figure 2) simplifies the interpretation of the environmental impacts and costs for a given product system through visualisation of the 'portfolio position' to determine eco-efficient options.

Figure 2 EE portfolio



EE portfolio values above the diagonal line are considered to be highly eco-efficient, as denoted by 'product X', whereas portfolio positions below the diagonal are considered eco-inefficient, as denoted by 'product Y'. For eco-inefficient products, cause-diagnosis and improvement strategies (e.g., design improvement, process improvement, raw material changes/input substitution, and technology changes/modification) are considered iteratively using follow up LCIAs and LCCs until the EE portfolio position goes above the diagonal line.

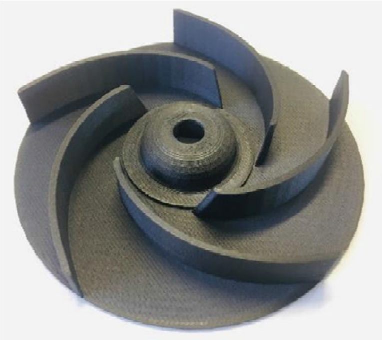
2.2 Implementation of the TEE framework

The following steps are involved in the implementation of the TEE framework.

2.2.1 Part selection and manufacturing for EE assessment

Firstly, a suitable part and materials were selected for additive manufacturing. A semi-open pump impeller was selected from a portfolio of a turbine impeller, spur gear, and closed pump impeller, based on a feasibility score that considered complexity (Peng et al., 2017; Paris et al., 2016; Fernández et al., 2016), solid-to-cavity/solid-to-envelope ratio (Ingarao et al., 2018; Watson and Taminger, 2018), application (Peng et al., 2017; Mami et al., 2017; Huang et al., 2016), functionality of the part (Serres et al., 2011), simplicity of the part (Yoon et al., 2014), and availability of standard performance testing criteria (Fernández et al., 2016). Pump impellers are complex-shaped critical components in pumps which are predominantly used in petrochemical, industrial, water supply and drainage applications. The impeller blades make it difficult to perform machining operations with a required level of dimensional tolerance and product quality. The quality of the impeller is thus a decisive factor that affects the operation of the entire equipment (Peng et al., 2017). 3D printing allows the manufacture of complex-shaped impellers without the need for additional machining processes. A semi-open pump impeller (Figure 3) from a Grundfos Unilift KP250 (0.5 kW, 2,900 rpm) submersible pump was considered for evaluating the TEE performance of 3D printed pump impellers. A mass production scenario was selected to determine the batch size. The original pump impeller was removed from the pump after disassembly, and a scanned 3D model was obtained using a *HP David SLS-1* structured light scanner. The scanned model was post-processed using *Autodesk Meshmixer* and *Solidworks* to obtain the final 3D model in .obj (object) and .stl (stereolithography) formats.

Figure 3 3D printed pump impeller (see online version for colours)



Pump impellers were fabricated through fused filament fabrication (FFF) using a *Markforged Mark 2* 3D printer (Figure 4). *Onyx* (short fibre carbon-nylon composite) material was used as the primary feedstock material for these impellers while fibreglass was used as the reinforcement material. As shown in Table 1, XYZ build-orientation with minimum bounding volume (International Organization for Standardization, 2013), 0.1 mm minimum layer height, and standard speed identified by the literature and *Eiger*© software were used for manufacturing. An isotropic fibre filling pattern was used for the continuous fibre reinforcement since reinforcement properties are similar in all directions. Process parameters such as infill pattern, infill rate, and reinforcement material were varied. A sample size of three impellers from each of the C, T, H, and F configurations was used. A fibreglass-reinforced configuration of 100% fibreglass infill was not considered due to printer constraints, time, and resource limitations.

Figure 4 Markforged Mark 2 3D printer used for manufacturing (see online version for colours)

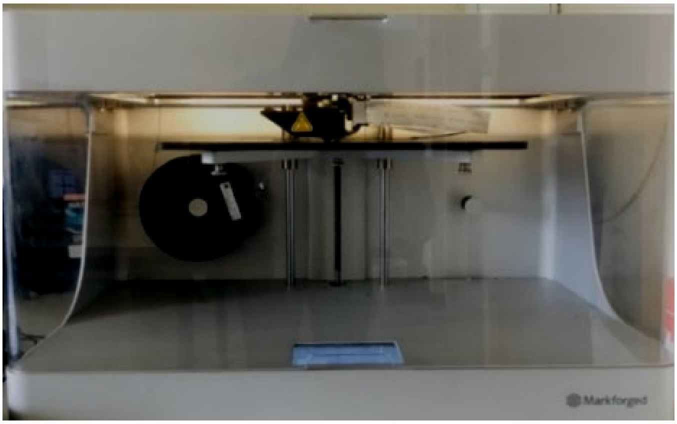


Table 1 Printing parameters used for manufacturing impellers

Parameter	*C*	*T*	*H*	*F*
Material	Onyx	Onyx	Onyx	Onyx
Infill (%)	100	50	50	100
Infill pattern	Solid	Triangular	Hexagonal	Solid
Roof and floor layers	4	4	4	4
Walls	2	2	2	2
Layer height (mm)	0.1	0.1	0.1	0.1
Reinforcement	-	-	-	Fibreglass
Fibre layers	-	-	-	8
Fibre fill pattern	-	-	-	Isotropic*
Concentric fibre rings	-	-	-	2
Fibre angles (°)	-	-	-	0, 45, 90, 135*

Notes: C: solid impeller, T: triangular infill impeller, H: hexagonal infill impeller and F: fibre-reinforced solid impeller. *In four directions (0, 45, 90 and 135 directions).

2.2.2 Technical feasibility assessment

The technical properties of 3D printed material are highly dependent on the manufacturing process due to its inherent anisotropy when compared to the bulk materials used in conventional subtractive manufacturing (International Organization for Standardization, 2014; Tymrak et al., 2014). Therefore, a technical feasibility assessment should be carried out by testing the technical properties of 3D printed materials and parts, in addition to hydraulic performance testing of the impellers.

The following fundamental properties, as outlined by ISO 17296-3 (International Organization for Standardization, 2014), were tested in order to ensure that the technical properties of the resulting 3D printed products were similar to those made of bulk materials.

2.2.2.1 Surface properties

- Surface roughness – This changes the magnitude of the hydraulic and frictional losses in the pump impeller by changing the flow properties (Fernández et al., 2016; Varley, 1961). Therefore, the mean surface roughness (R_a) of the impeller shrouds and vanes were measured using a *Mitutoyo SJ-201* profilometer. The surface roughness of machined nylon 6/6 was considered for comparison/benchmarking.

2.2.2.2 Geometric properties

- Dimensional tolerance – This ensures fitting and clearance of the impeller in the pump assembly. Improper fits can cause vibration, resulting in impeller failure (Peng et al., 2017). Therefore, dimensional tolerances of the inner diameter, outer diameter, vane thickness, and shroud thickness of the impeller were measured using a *Mitutoyo RDL058* digital vernier calliper. The tolerances for machined nylon 6/6 were considered for comparison/benchmarking.

2.2.2.3 Mechanical properties

- Tensile test – Tensile properties of a material indicate the material's response to withstand deformation due to tensile stresses. Higher tensile properties of the impeller imply improved durability and SL due to lower deformation. The specimens in each configuration were tested according to the AS 1145.4 standard using a *Shimadzu Autograph* universal testing machine with a load cell of 50 kN at a strain rate of 5 mm/min to calculate the yield stress, ultimate tensile stress (UTS) and Young's modulus.
- Fatigue test – This determines the number of cycles to failure under a given load which indicates the life of the pump impeller. A higher number of cycles to failure imply higher durability and SL. It was deemed particularly important for sustainability as it could help select the impeller with increased lifetime and resulting resource efficiency. Therefore, according to the ASTM D7791-17 standard, fatigue cycles to failure of test specimens were measured using an *Instron 8801* universal testing machine. The standard procedure suggests testing of the material at different percentages of UTS obtained from tensile tests, i.e., 90%, 85% and 80% of UTS. Three specimens for each stress level were tested at a frequency of 1 Hz with a stress

ratio (R) of 0.1 for each configuration, namely C, T, H and F. The results were used to draw S-N curves for the materials using the Basquin equation [equation (1)] for the finite region of the fatigue life of the impellers. *S* is the applied cyclic tensile stress, *N* is the number of cycles to failure, and *A* and *B* are material constants related to UTS and dynamic hardening modulus (Pertuz et al., 2020). Fatigue strength of nylon 6/6 bulk material was considered for comparison. Since the real operational conditions are complex, a simple fatigue life estimation of the impellers was obtained from the product of *N* and pump speed [equation (2)].

$$S = A \times N^B \tag{1}$$

$$Estimated\ \ fatigue\ life\ (h) = N \,/\, Pump\ speed\ \text{(cycles/h)}. \tag{2}$$

2.2.2.4 Build material properties

- Macrostructure – The macrostructure of the material was used to explain the technical properties such as mechanical strength of the impeller. A higher number of defects and porosity in the macrostructure affects technical properties (Pertuz et al., 2020). Therefore, the macrostructure of specimen fracture surfaces was investigated using an *Olympus BX51* light microscope. However, comparisons were not made since voids and defects were not quantified.
- Product density – Product density is an important measurement in 3D printed parts due to the formation of voids in the layer by layer manufacturing (Terekhina et al., 2019). The density of the feedstock material (Onyx) was compared with the density of the solid (Onyx) impellers (C1, C2, C3) to identify defects in 3D printing. Therefore, product density was measured using the specific gravity method according to the AS 1141.5-2000 standard.

2.2.2.5 Hydraulic performance test

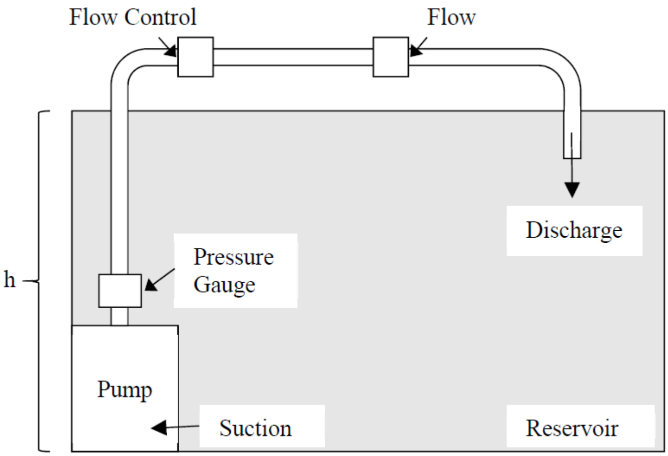
A hydraulic performance test for each pump impeller was conducted according to ISO 9906: *hydraulic performance acceptance test for rotodynamic pumps* (International Organization for Standardization, 2012). The impeller was fitted to the pump and then tested in a recirculating pump test rig (Figure 5) to obtain head (H) vs. flow rate ($\dot{Q}$) curves (pump performance curves) for complete test cycles. The static suction head (H_s) was calculated by the water level [equation (3)] at the point of suction, whilst a pressure gauge was used to measure the head at the point of discharge (H_d). The pump head ($H_{pump,n}$) was calculated [equation (4)] assuming no head losses in the system (n – type of impeller, h – suction height, ρ_w – density of water, g – acceleration due to gravity). The flow rate was calculated using a flowmeter and a stopwatch. The results were plotted in MS Excel to determine the pumping performance of the impeller.

$$H_s = h \times \rho_w \times g \tag{3}$$

$$H_{pump,n} = H_{d,n} - H_s \tag{4}$$

The pumping performance of each impeller was calculated using the results of the H_{pump} vs. $\dot{Q}$ curve of each impeller to determine the energy consumption for a given H_{pump}. The variation between the pump performance curves was compared/benchmarked with the original equipment manufacturer (OEM) pump impeller.

Figure 5 Hydraulic performance test rig



2.2.2.6 *Benchmark and overall technical feasibility assessment*

Nylon 6/6 is a common material used in the manufacture of pump impellers due to its good technical properties and lower manufacturing costs (Wankhade and Jarikote, 2019). Therefore, the technical feasibility of the 3D printed impellers was assessed by benchmarking with the technical properties of nylon 6/6 bulk material whilst the performance curve of a nylon 6/6 pump impeller was used for benchmarking the hydraulic performance.

2.3 *Environmental life cycle assessment*

After the technical feasibility assessment, the ELCA of technically feasible impellers was carried out according to the ISO 14040-44 standard (International Organisation for Standardization, 2006). The functional unit (FU) of this ELCA was an impeller delivering fluid over its useful life. The scope would cover the 'conception to use' stages of its life cycle, i.e., design, material processing, manufacture, use of the impeller, and transportation between stages, as shown in Figure 6. The energy, materials, utility, and labour inputs and waste and emission outputs associated with impeller production were considered. The use stage product SL estimate of each technically feasible impeller as explained in the fatigue test section was used for the calculation of use stage life cycle inputs of the impeller. The end-of-life stage of the pump impeller was not considered in the scope of the LCA in order to focus on the feasibility assessment of 3D printed products.

A LCI was developed for each impeller *n* as this was a pre-requisite to carrying out a life cycle environmental assessment. LCI consists of inputs in the form of energy and materials used in all stages of the impeller life cycle. Once the LCI of an impeller had been developed, the inputs were incorporated into SimaPro LCA software to calculate the environmental impacts (Arceo et al., 2019). The software provides values for all individual environmental impacts, but the authors only used those which are relevant to the manufacturing industry in Australia. These impacts were selected through a consensus survey by interviewing local manufacturing experts. Thirty respondents from three categories (academia, industry and government) of stakeholders across Australia were surveyed. The respondents were also required to rank these impacts which were used to determine the normalised weights (W_i) of these impacts for EE analysis. The corresponding weights for each environmental impact were calculated [equation (5) and equation (6)] following Lim and Biswas (2018) and have been presented in Table 2.

$$Wj = nj1 * 1 + nj2 * 2 + nj3 * 3 + nj4 * 4 + nj5 * 5 \tag{5}$$

$$Wi = Wj / W_{tot} * 100 \tag{6}$$

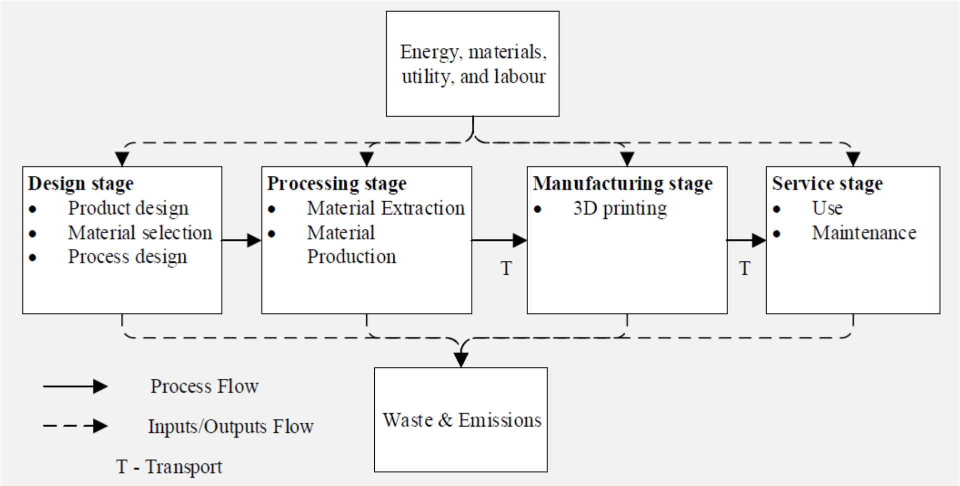
j	1, 2, 3, …, M (environmental impact indicator)
$nj1$	no. of 'no responses' for j
$nj2$	no. of 'somewhat important' responses for j
$nj3$	no. of 'moderately important' responses for j
$nj4$	no. of 'important' responses for j
$nj5$	no. of 'very important' responses for j
W_{tot}	sum of all weights (W_j) for M number of indicators.

Table 2 Normalisation factors and corresponding weights of the environmental impacts

Environment impacts (EIs)	*$GDEI_i$*	*Unit (per inhabitant/y)*	*Weight (Wi)*
Global warming potential (GWP)	28,690	t CO_2 eq.	11.44%
Photochemical smog	75	kg NMVOC	9.06%
Particulate matter	45	kg $PM_{2.5}$ eq.	10.42%
Eutrophication	19	kg PO_4^{3-} eq.	9.51%
Human	3,216	kg 1,4-DB eq.	10.08%
Terrestrial	88	kg 1,4-DB eq.	10.08%
Freshwater	172	kg 1,4-DB eq.	10.08%
Marine	12,117,106	kg 1,4-DB eq.	10.08%
Land use	26	Ha a	8.83%
Acidification potential	123	kg SO_2 eq.	8.38%
Abiotic depletion potential (ADP)	300	kg Sb eq.	9.85%
Water use	930	m^3 H_2O	10.99%
Cumulative energy demand (CED)	246,900	MJ	11.44%

Note: CO_2 – carbon dioxide, NMVOC – non-methane volatile organic compound, $PM_{2.5}$ – particulate matter, PO_4^{3-} – phosphate, DB – dichlorobenzene, Ha a – hectare per year, SO_2 – sulphur dioxide, Sb – antimony, H_2O – water, eq. – equivalent and MJ – megajoule.

Figure 6 The scope of ELCA



The environmental impacts that were selected through this survey were global warming potential, eutrophication, land use, water use, cumulative energy demand, acidification potential, abiotic depletion potential, photochemical smog, particulate matter and eco-toxicity. The eco-toxicity impact was calculated based on the individual values of human, terrestrial, freshwater, and marine toxicity. First five aforementioned impacts were calculated using Australian indicator set with embodied energy V2.01, but next two impacts were calculated following EPD (2013) V1.02, then next two impacts were calculated using ILCD 2011 Midpoint + V1.08 method and then the remaining impacts were calculated using CML-IA baseline V3.03 as the Australian indicator set does not allow the calculation of these six impacts.

2.4 *Life cycle costing*

After the ELCA, LCC was conducted. The goal, scope, and LCI of the LCC were the same as ELCA to ensure both LCEI and LCCs have the same denominator and incorporate the same system boundary in order to determine the EE (Kicherer et al., 2006). The final LCC was represented in terms of AUD per impeller of each configuration so that the denominators for both ELCA and LCC were the same. The LCC was conducted according to the AS/NZS 4536:1999 Australian/New Zealand Standard for LCC – application guide (Standards Australia/Standards New Zealand, 1999). The inputs in the LCI were first incorporated into Microsoft Excel for LCC analysis. A market survey was conducted to convert the inputs to corresponding cost values. Only one cost item that was not in the LCI (i.e., labour) was included for the LCC analysis. A detailed cost model that was incorporated for cost estimation for all life cycle stages consists of two steps: LCC impeller production and LCC pump use. End-of-life disposal costs were not included to match the scope of the ELCA.

Step 1 The impeller production included the economic analysis of design, material processing, and manufacturing stages in terms of capital, labour, energy, operations and maintenance and transportation [equation (7)]. The design stage costs included CAD modelling, process design, material selection and other utility costs obtained through a market survey (PayScale, 2020). The material processing stage costs included the cost of material (Markforged, 2020b) and transportation costs from Boston, USA to the 3D printing facility in Australia (Australian Government, 2015). The manufacturing stage costs included the energy consumption (Canstar Blue, 2020), 3D printer equipment costs (Markforged, 2020a), and labour costs (Australian Bureau of Statistics, 2018) apportioned to the print time for each impeller. Furthermore, sunk costs such as the cost of indirect machinery, equipment, and lease/rent on the property were not evaluated since it would not influence decision making (Mami et al., 2017). A mass production scenario was assumed for the production of 3D printed F impeller considering two 3D printers with a lifetime of five years and the same production scenario for the N impeller considering one CNC machine with a lifetime of ten years [equation (7)]. A capital recovery factor (*CRF*) was used to convert the sum of present values (*PVs*) into annuitised cost (*AC*) and they were divided by annual production output (*PO*) to obtain the LCC production cost per impeller [equation (7)]. ACs are series of annual cash flows. A profit mark-up (*PM*) of 35% was used to convert LCC to the price of the impeller (*PI*) (Plumbing and Mechanical, 2000) [equation (8)].

$$LCC_{Impeller,prod.} = \left(PV_{capital} + PV_{Labour} + PV_{Energy} + PV_{O\&M}\right) \times CRF / PO \tag{7}$$

$$PI = LCC_{Impeller,prod.} \times (1 + PM) \tag{8}$$

Step 2 The pump usage included the economic analysis of impeller usage stage. The timeframe of this LCC was the SL of the technically feasible impeller. This SL of the pump impeller was based on the fatigue life as discussed in the technical feasibility assessment section. The $LCC_{pump\ usage}$ includes the capital costs of pump impeller which is the PI as determined using equation (8) and the operating costs (i.e., energy consumption). The maintenance costs were avoided since pump impellers require minimum maintenance. An inflation rate of 1.90% in Australia was incorporated into both sections of LCC calculations (Trading Economics, 2020). The calculated costs were discounted to the PV in 2020 with a discounting factor of 7% (Department of the Prime Minister and the Cabinet, 2016), to reflect time value of money, uncertainties, and risks in the manufacturing industry. The PVs of the capital and operating costs of pumping were multiplied by CRF to convert to AC and then divided by the SL of the impellers as presented in equation (9) in order to obtain the LCC of pumping over impeller SL ($LCC_{P,SL}$).

$$LCC_{P,SL} = \left(PV_{PI} + PV_{energy}\right) \times CRF / SL. \tag{9}$$

2.5 EE portfolio

The environmental life cycle impacts were normalised and weighted to determine the dominant environmental impacts. The individual normalisation factors were developed considering environmental impacts per Australian inhabitant per year (Department of the Environment and Energy, 2019; Bengtson and Howard, 2010) and weighting factors were developed from the consensus survey, as shown in Table 2.

Individual $GDEI_i/Inh$ values for human, terrestrial, freshwater, and marine toxicity were used to normalise the eco-toxicity values. EE portfolio positions are used in the EE analysis to compare the economic and environmental performance products. Both LCEI and LCC values of 3D printed impellers were used to calculate the EE portfolio positions of 3D printed impellers using (Arceo et al., 2019). LCEI values of the pump impeller type *n* were normalised [equation (10)] by dividing with relevant $GDEI_i/Inh$ to obtain the normalised value of environmental impact ($NEI_{i,n}$). $NEI_{i,n}$ was multiplied with their corresponding weights (W_i) [equation (11)] for each impact category *i* in order for all impacts to add to obtain a single score of environmental impact (EI_n) for an impeller *n* (Arceo et al., 2019). In other words, this EI_n was represented as the number of Australian inhabitants producing equivalent environmental impact created by the impeller type *n*.

$$NEI_{i,n} = \frac{LCEI_{i,n}}{GDEI_i / Inh} \tag{10}$$

$$EI_n = \sum_{i=1}^{11} NEI_{i,n} \times W_i \tag{11}$$

The life cycle costs (LCC_n) of pump impeller *n* were normalised [equation (12)] to obtain the normalised costs (NC_n) by dividing with the relevant Australian GDP per inhabitant (GDP/Inh) obtained from a GDP of AUD1.89E+12 (Australian Bureau of Statistics, 2020) and a population of 2.55E+07 inhabitants (Australian Bureau of Statistics, 2019). This NC_n was represented as the number of Australian inhabitants producing equivalent GDP to the cost of the impeller *n*.

$$NC_n = \frac{LCC_n}{GDP / Inh} \tag{12}$$

The preliminary portfolio positions [equation (13) and equation (14)] of each impeller *n* were determined by dividing the normalised impact and normalised cost of each impeller by average values of EIs and NCs of all impellers to develop the relationship between impellers under consideration.

$$PP_{e,n} = \frac{EI_n}{\sum EI_n / j} \tag{13}$$

$$PP_{c,n} = \frac{NC_n}{\sum NC_n / j} \tag{14}$$

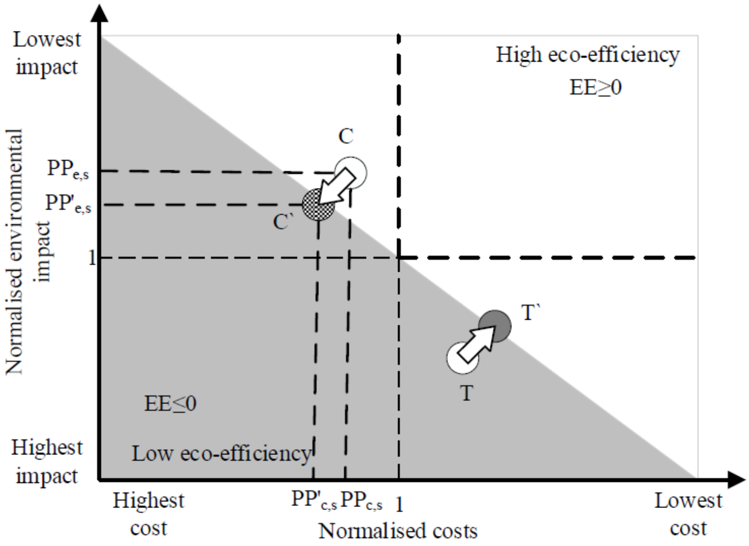
$R_{E/C}$ [equation (15)], which was the ratio of mean *EI* and mean *NC*, was used in the portfolio to establish whether the cost was more influential than the environmental impact. Following Arceo et al. (2019), the preliminary portfolio positions were improved by the $R_{E/C}$ to obtain a balance of cost and impact [equation (16)]. The improved portfolio positions ($PP'_{e,n}$, $PP'_{c,n}$) were plotted in the EI_n vs. NC_n graph (Figure 7).

$$R_{E/C} = \frac{\sum EI_n / j}{\sum NC_n / j} \tag{15}$$

$$PP'_{e,n} = \frac{\left[\left(\sum PP_{e,n}\right)\Big/ j + \left[PP_{e,n} - \left(\left(\sum PP_{e,n}\right)\Big/ j\right)\right] \cdot \sqrt{\left(R_{E/C}\right)}\right]}{\left(\sum PP_{e,n}\right)\Big/ j} \tag{16}$$

$$PP'_{c,n} = \frac{\left[\left(\sum PP_{c,n}\right)\Big/ j + \left[PP_{c,n} - \left(\left(\sum PP_{c,n}\right)\Big/ j\right)\right] \Big/ \sqrt{\left(R_{E/C}\right)}\right]}{\left(\sum PP_{c,n}\right)\Big/ j} \tag{17}$$

Figure 7 EE portfolio and positions



The most eco-efficient option in this EE portfolio had the largest perpendicular distance above the diagonal line. Equations (16)–(17) show that any changes to an EE portfolio position of one impeller could change the position of all impellers due to the incorporation of the $R_{E/C}$. Impellers that fell below the diagonal line were considered eco-inefficient and required further environmental and/or economic improvements to stay on or above the diagonal line.

2.6 Limitations

- 3D printing was limited to the FFF of composite materials using a Markforged Mark 2 printer.
- The 3D printed part design was obtained from an OEM part, hence benefits of topology optimisation to 3D printing were not explored.

- The failure rate of 3D printers in mass manufacturing compared to mass manufacturing of CNC machined parts was not considered in the study as the research conducted in the laboratory mainly focusing on the mechanical and structural properties of the 3D printed impellers.
- The single score environmental impact results (normalising, weighting, and aggregating endpoint environmental impacts) entailed certain uncertainties while presenting a simple method for comparative assertions.
- The social impacts of 3D printing were not incorporated in this study due to resource and time constraints.

3 Results and analysis

3.1 Technical feasibility assessment

3.1.1 Surface roughness

The average values of the 3D printed impellers were compared with R_a of N. The values of the 3D printed impellers were slightly higher than the R_a of N as shown in Table 3 due to significant print lines from 3D printing. Furthermore, values of the 3D printed impeller vanes were higher than the values of the 3D printed impeller shroud, which was due to better layer stacking in the XY direction compared to the weaker layer stacking in the Z direction when 3D printing the vanes. The values of 3D printed impellers were deemed feasible compared to the benchmark values.

Table 3 Mean surface roughness measurements

Impeller	*Shroud R_a (μm)*	*Deviation (μm)*	*Vane R_a (μm)*	*Deviation (μm)*
S1	4.612	1.412	11.444	8.244
S2	4.437	1.237	7.684	4.484
S3	4.819	1.619	8.078	4.878
T1	4.599	1.399	10.464	7.264
T2	4.633	1.433	11.332	8.132
T3	4.618	1.418	11.060	7.860
H1	6.179	2.979	10.714	7.514
H2	6.171	2.971	8.812	5.612
H3	6.093	2.893	11.530	8.330
F1	5.123	1.923	12.134	8.934
F2	5.602	2.402	12.064	8.864
F3	5.541	2.341	12.266	9.066
N	3.200		3.200	

3.1.2 Dimensional tolerance

Inner diameter, outer diameter, vane thickness, and shroud thickness were measured using a *Mitutoyo RDL058* digital vernier caliper with a minimum error of 0.05 mm. There were variations of the printed specimens from the 3D model of the impellers. The outer diameters of the printed impellers were undersized whereas all other dimensions were found to be oversized (Table 4). The dimensional tolerances were compared with ±0.125 mm standard dimensional tolerance of machined nylon. The 3D printed impellers had acceptable tolerances in all the features as presented in Table 5.

Table 4 Dimensional measurement

Impeller	*Inner diameter (mm)*	*Outer diameter (mm)*	*Vane thickness (mm)*	*Shroud thickness (mm)*	*Height (mm)*
C1	8.05	90.50	1.65	1.05	13.05
C2	8.05	90.60	1.70	1.10	13.00
C3	8.10	90.50	1.65	1.00	13.00
T1	8.00	90.45	1.60	1.05	13.10
T2	8.00	90.60	1.65	1.10	13.00
T3	8.00	90.45	1.70	1.10	13.00
H1	8.00	90.45	1.60	1.00	13.10
H2	8.05	90.50	1.75	1.00	13.05
H3	8.00	90.60	1.70	1.05	13.00
F1	8.05	90.60	1.70	1.10	13.10
F2	8.00	90.60	1.60	1.10	13.00
F3	8.00	90.50	1.60	1.10	13.15
OEM spec	8.00	90.00	1.60	1.10	13.00

Table 5 Dimensional tolerances of the 3D printed impeller features

Parameter	*Value*
Inner diameter	±0.050 mm
Outer diameter	±0.075 mm
Vane thickness	±0.075 mm
Shroud thickness	±0.050 mm
Height	±0.075 mm

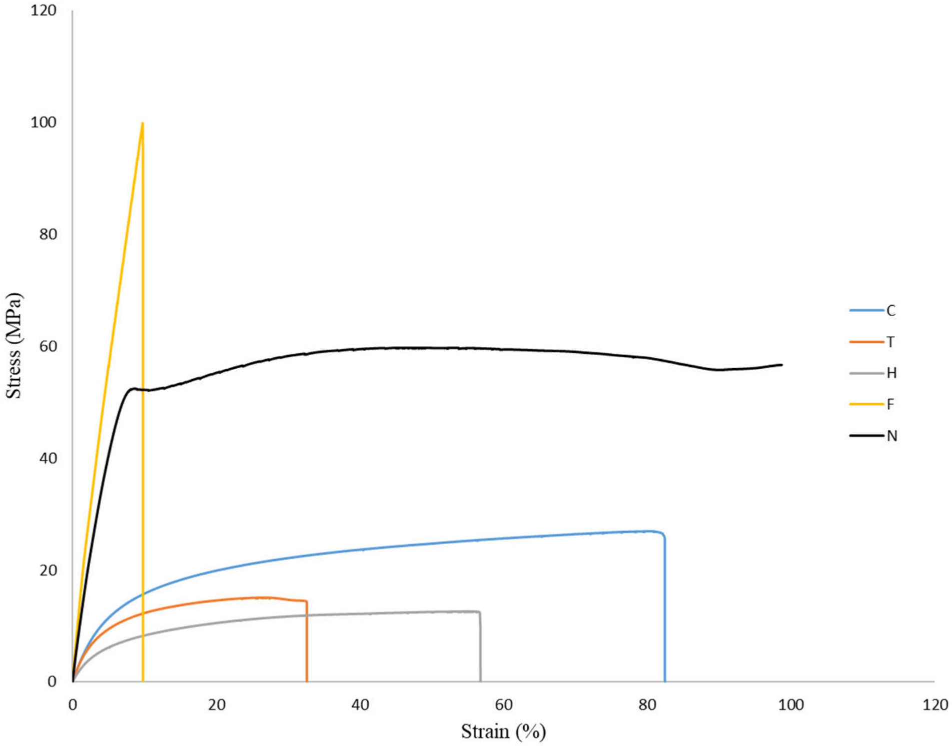
Table 6 Tensile results

Specimen	*Yield point (MPa)*	*Ultimate tensile strength (MPa)*	*Elastic modulus (GPa)*	*Percentage elongation at break (%)*
C	14	28	0.23	84
T	8	15	0.26	35
H	6	13	0.30	58
F	100	100	1.11	9
N	54	60	0.67	-

3.1.3 Tensile test

Tensile results as presented in Table 6 indicated the presence of ductile failure for C, T, H specimens similar to the properties of N. In contrast to this, the tensile results of F specimen exhibited brittle failure similar to the properties of fibreglass. The lowest tensile properties were shown by H specimen whilst all the unreinforced specimens indicated lower properties compared to nylon 6/6. However, the tensile tests for all C, T, H, F specimens exhibited uniform results over all samples. Figure 8 presents the representative results of all the tensile tests.

Figure 8 Representative stress vs. strain curves for all configurations (see online version for colours)



3.1.4 Fatigue test

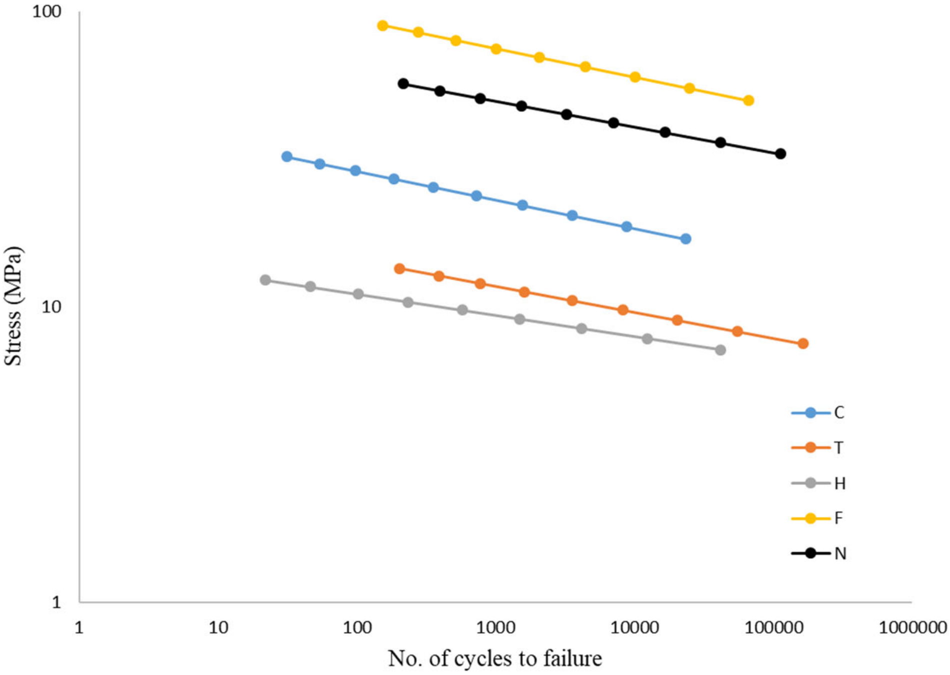
The fatigue results were obtained in the finite life region below 1,000 cycles to failure. At 90%, 85%, and 80% of the UTS, samples of all configurations failed below 1,000 cycles. The data were fitted using Basquin's model [equation (18)] and the following S-N curves were obtained for all configurations (Figure 9). The respective intercept (*A*) and gradient (*B*) values of the curves are shown in Table 7. F samples exhibited the highest fatigue properties while H samples showed the lowest fatigue properties.

$$\log S = B \times \log N + \log A \tag{18}$$

Table 7 Basquin's model values for the extrapolated curves

	C	*T*	*H*	*F*	*N*
A	45.09	21.53	14.45	146.45	91.08
B	–0.097	–0.0879	–0.0567	–0.0968	–0.0873

Figure 9 S-N curves for all configurations (see online version for colours)



3.1.5 Fatigue life estimation

The fatigue life of the 3D printed parts was estimated using the S-N curves considering a 10 MPa pressure load acting on the pump impellers under normal operations. Table 8 presents the fatigue life estimations of the impellers.

Table 8 Fatigue life of impellers

Configuration (n)	*No. of cycles to failure*	*Fatigue lifetime-estimate (h)*
C	5,534,714	31.808
T	6,150.31	0.035
H	659.99	0.004
F	1.10E+12	6.33E+06
N	9.77E+10	5.62E+05

Both F and N specimens exceeded the fatigue limit under the 10 MPa pressure load. This implies that the impeller SL is determined by other failure mechanisms such as foreign object damage or cavitation. Hence, an equal product life of '200 hours' was estimated for both F impeller and N impeller using available literature for nylon impeller replacement for a submersible pump in drainage applications with high foreign object damage. A pump usage of 2 h per day for 20 days a month (5 months) was estimated for F impeller for life cycle calculations (West Marine, 2019; Strongman Pumps, 2020). The fatigue lifetime estimations of C, T, H impellers were below the acceptable values due to fatigue failure.

3.1.6 Fracture surface investigation

The fracture surfaces of the fatigue specimens showed the presence of distinctive material layers due to layer by layer deposition of material in 3D printing. Further magnification of the fracture surfaces indicated the presence of short fibres protruding from the Onyx material. Fracture of the C specimens (Figure 10) was found to propagate along the XY layers which can be observed from the surface topography (Figure 11).

Figure 10 Fracture surface of C (see online version for colours)

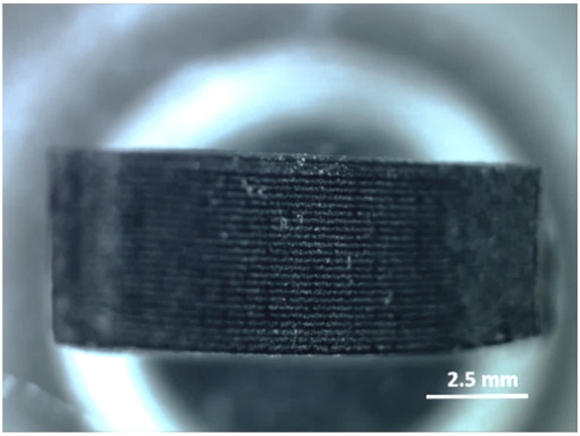


Figure 11 Surface topography of C (see online version for colours)

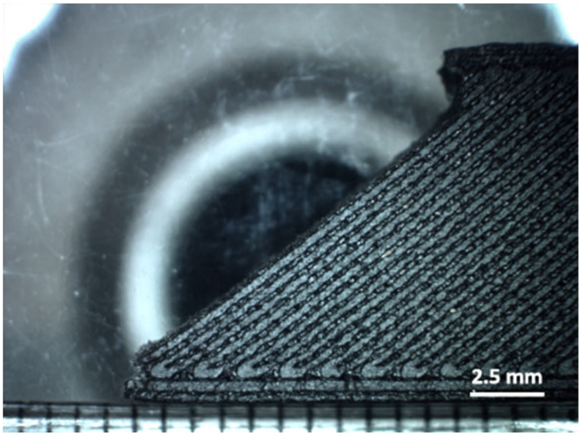


Figure 12 Fracture surface of T (see online version for colours)

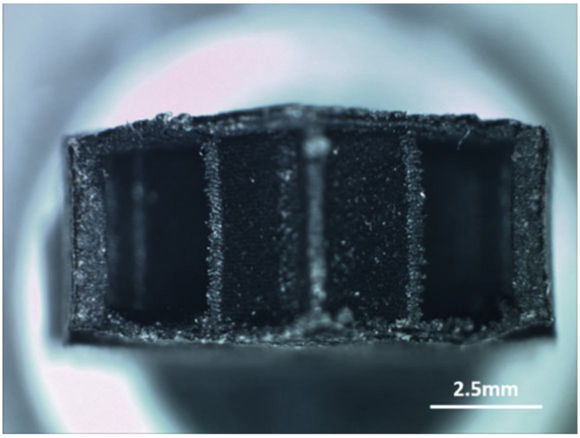


Figure 13 Surface topography of T (see online version for colours)

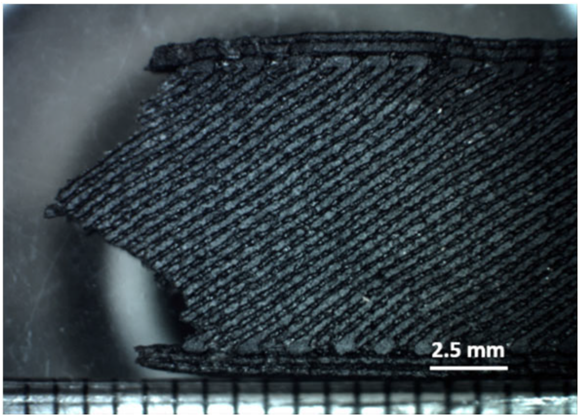


Figure 14 Fracture surface of H (see online version for colours)

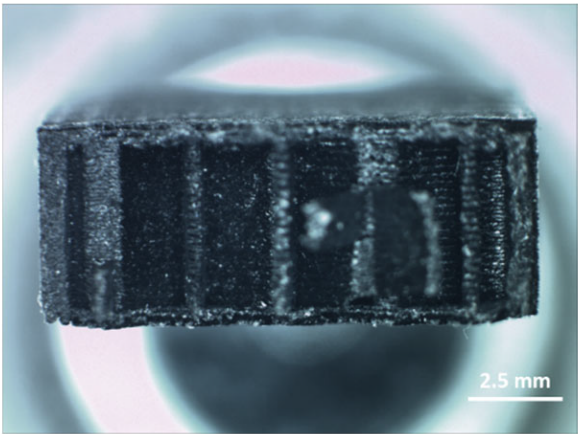


Figure 15 Surface topography of H (see online version for colours)

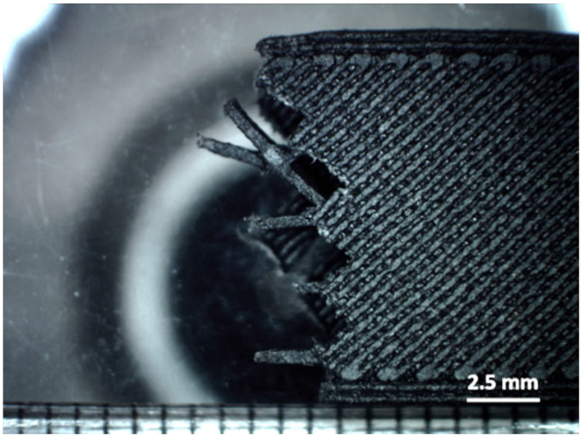


Figure 16 Fracture surface of F (see online version for colours)

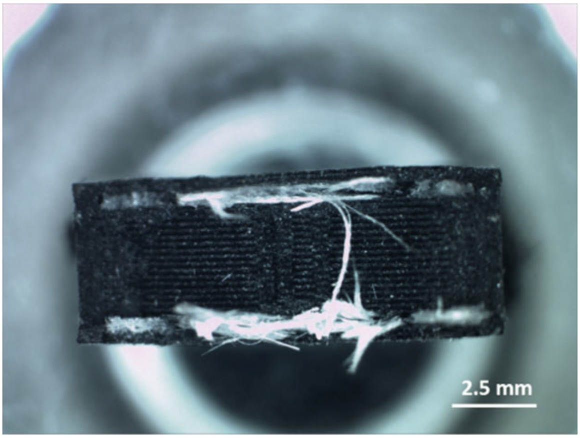
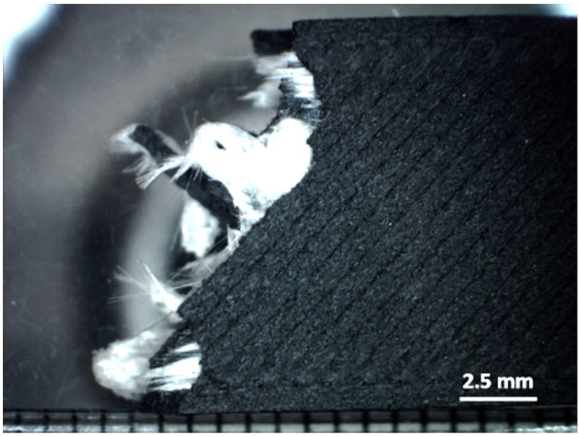


Figure 17 Surface topography of F (see online version for colours)



The fracture surface of T specimens (Figure 12 and Figure 13) suggested that fracture had propagated along the lines of infill geometry. The internal geometry of the T specimens contributed to the fracture whilst the XY layers had a lower effect on crack propagation.

Fracture analysis of the H specimens (Figure 14 and Figure 15) also exhibited similar behaviour to the T specimens. However, the internal geometry, as well as the XY layers, contributed to fracturing which then resulted in lower fatigue properties.

Fracture analysis of the F specimens (Figure 16 and Figure 17) indicated the presence of glass fibres in the roof and wall layers of the specimen. Brittle failure of glass fibres resulted in the failure of the Onyx material which was similar to the C specimens. The fatigue properties of the Onyx material were noted to have been significantly increased due to the presence of this glass fibre reinforcement.

3.1.7 Density testing

Density test results showed that the mean product density of impeller samples was 1.18 g·cm^{-3} whereas the material density of Onyx was 1.20 g·cm^{-3} with a variation of 1.67% (measured at 22.9°C). The lower variance in product density and material density shows the minimal presence of internal voids and defects in the 3D printed product.

3.1.8 Hydraulic performance test

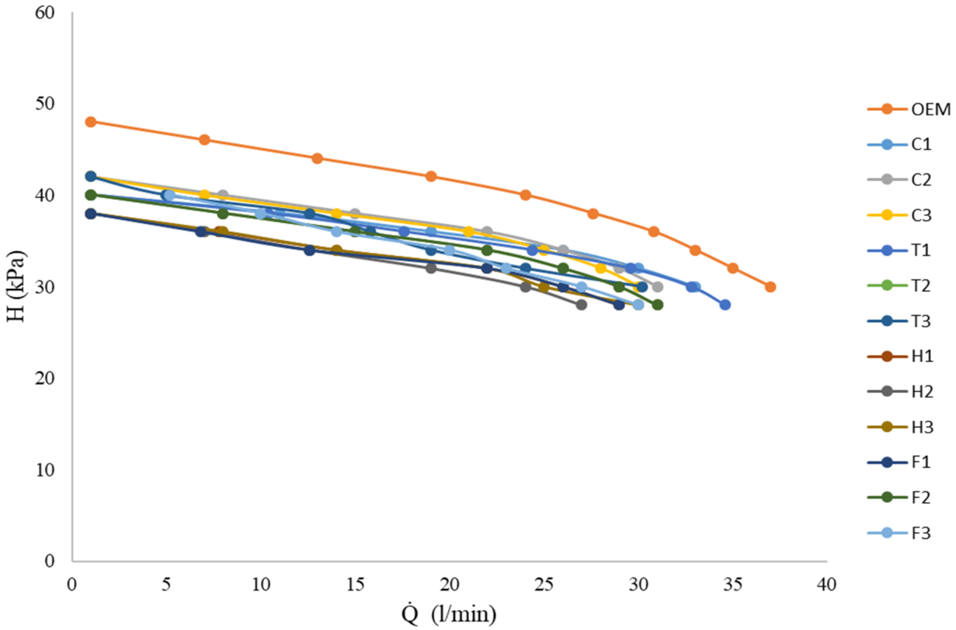
Table 9 presents the results of the hydraulic performance test. The results were plotted on H vs. $\dot{Q}$ curves as illustrated in Figure 18 to measure the hydraulic performance of the pump impellers. Since conventional nylon impeller data is available, the experiment was not conducted for nylon. The highest performance was shown by the OEM impeller due to the lower surface roughness. The effect of surface roughness on the hydraulic performance of 3D printed (FFF) impellers was similar to the results of Fernández et al. (2016). However, the 3D printed impellers also showed uniform hydraulic performance throughout all configurations.

Table 9 Hydraulic performance results

	H (kPa)	*28*	*30*	*32*	*34*	*36*	*38*	*40*	*42*	*44*	*46*	*48*
$\dot{Q}$ (l/min)	OEM	-	37.0	35.0	33.0	30.8	27.6	24.0	19.0	13.0	7.0	1.0
	C1	-	33.0	30.0	26.0	19.0	11.0	1.0	-	-	-	-
	C2	-	31.0	29.0	26.0	22.0	15.0	8.0	1.0	-	-	-
	C3	-	30.0	28.0	25.0	21.0	14.0	7.0	1.0	-	-	-
	T1	34.6	32.8	29.6	24.4	17.6	10.4	1.0	-	-	-	-
	T2	31.0	29.0	26.0	22.0	15.0	8.0	1.0	-	-	-	-
	T3	-	30.2	24.0	19.0	15.8	12.6	5.0	1.0	-	-	-
	H1	29.0	26.0	22.0	14.0	7.8	1.0	-	-	-	-	-
	H2	27.0	24.0	19.0	12.6	7.0	1.0	-	-	-	-	-
	H3	30.0	25.0	22.0	14.0	8.0	1.0	-	-	-	-	-
	F1	29.0	26.0	22.0	12.6	6.8	1.0	-	-	-	-	-
	F2	31.0	29.0	26.0	22.0	15.0	8.0	1.0	-	-	-	-
	F3	30.0	27.0	23.0	20.0	14.0	10.0	5.2	1.0	-	-	-

Note: 1, 2 and 3 – sample numbers of impellers.

Figure 18 H vs. $\dot{Q}$ curve for all impellers (see online version for colours)



The infill density and fibre reinforcement did not affect the pump performance curve of the impellers. However, when the impellers were kept in the performance test rig for 0.5 h, the H impeller showed a performance variation over time whereas F impeller showed no performance variation. Upon visual inspection, H impeller showed deformation over time, which was due to the influence of lower tensile and fatigue properties as previously observed.

3.1.9 Overall technical feasibility assessment

Table 10 shows the summary of a comprehensive technical feasibility assessment that was conducted to determine dimensional properties, surface properties, tensile properties, fatigue properties and hydraulic performance in order to validate the overall technical feasibility of 3D printed parts.

Table 10 Overall technical feasibility

Parameter	*C*	*T*	*H*	*F*	*N*
Surface roughness (R_a)	4.623	4.617	6.148	5.422	3.200
Density (g/cm^3)	1.18	-	-	-	1.15
Dimensional tolerance (mm)	±0.075	±0.075	±0.075	±0.075	±0.125
Tensile strength (MPa)	14	8	6	100	54
Fatigue strength (MPa)	17	7.5	6.5	50	30

The dimensional tolerance of all 3D printed parts was within acceptable tolerance levels, which ensured sufficient fit and clearance in the pump assembly. The pump impellers C, T, and H showed lower tensile and fatigue properties when compared to the nylon 6/6 bulk material benchmark properties. The lower tensile properties of these components were attributed to the weak interactive forces between layers and printed lines in the surface topography. The lower fatigue properties were due to the lower UTS values. The lowest ultimate tensile strength of 13 MPa was shown by the 50% hexagonal infill (H) specimen. However, the specimens with continuous fibre reinforcement (F) showed better results compared to the nylon 6/6 bulk material (N) benchmark. Similar studies comparing mechanical properties of Onyx material with different infill configurations (Bárnik et al., 2019a) had also found the lowest technical performance with lower infill density and hexagonal infill configuration.

The reasons for the lower technical properties of C, T, and H 3D printed specimens compared to the nylon 6/6 benchmark properties were investigated through fracture surface analysis of test specimens. The fracture surface topography showed that the cracks propagated along the print lines of the surface for all the specimens. The hexagonal and triangular infill specimens showed that the geometry of the internal structure affected the crack propagation, thereby resulting in lower UTS values. Furthermore, fracture surface analysis indicated the presence of voids, defects and porosity between the 3D printed layers in the C, T and H specimens. The presence of continuous fibre along the surfaces of the F specimens resulted in a significant reinforcement effect that was accompanied by improved tensile and fatigue properties. The density analysis of the 3D printed impellers showed that the variation between the density of the 3D printed material and the density of the Onyx material was 1.67%. This variation supports the presence of voids, defects and significant porosity observed by the optical analysis. The hydraulic performance of the 3D printed impellers was compared to the original stainless steel impeller with the same vane profile. The 3D printed impellers showed lower hydraulic performance (C – 14%, T – 16%, H – 22% and F – 19%) compared to the stainless steel impeller due to the lower surface roughness of the stainless steel sheet metal surface (He et al., 2019; Fernández et al., 2016). However, the results of the hydraulic performance test were consistent for all the impellers with minor variations due to variations in surface properties.

Only pump impeller F was found to be technically feasible in terms of dimensional tolerance, surface roughness, tensile properties, fatigue properties and hydraulic performance. Therefore, EE of pump impeller F was evaluated so as to consider economic and environmental aspects with the benchmark of CNC machined nylon 6/6 impeller (N) data obtained from the literature.

3.2 Environmental life cycle assessment (ELCA)

Once technically feasible 3D printed impellers have been selected, ELCA of a single impeller was conducted for each configuration in order to estimate 11 environmental impacts, as listed in Table 2. The annual batch size was calculated based on the assumption that the machines operated 8 h/day for five years with an annual utilisation factor of 90% (Modern Machine Shop, 2002). Mass manufacturing scenario was considered for the five year lifetime of the 3D printer. The LCI values of the 3D printer were apportioned based on the time for printing a 3D printed impeller. A similar mass manufacturing scenario involving a CNC machine utilisation/subtractive manufacturing was considered to determine the batch size of the N impeller for benchmarking purposes. The subtractive manufacturing was considered to continue for the ten years lifetime of the CNC machine. The LCI values of the CNC machine were apportioned to nylon impellers based on the total manufacturing time. The annual PO of F and N impellers manufactured from additive and subtractive manufacturing have been presented in Table 11.

Table 11 PO of impellers

Parameter	*F*	*N*
Total manufacturing time (hours)	4.78	4.48
Annual production output (PO)	549	586

Table 12 presents the LCIs of the 3D printed F impeller and subtractive manufactured N impeller, which consist of material, energy, and transportation values estimated over the design to production stages of the impeller. The use stage energy consumption of each impeller was calculated from the pump usage data obtained from the hydraulic performance testing. The fluid delivered over the useful estimated life of each impeller was incorporated into the analysis to assess the variation in their technical and EE performance.

Table 12 LCI of 3D printed impellers

Material/process	*Units*	*F*	*N*	*3D printer*	*CNC machine*
Sea transportation	tkm	0.42	2.80	271.00	87,802.11
Land transportation	tkm	0.01	0.02	0.52	396.00
Nylon	g	16.27	17.38	-	-
Carbon fibre	g	1.63	-	-	-
Fibre	kg	2.10	-	-	-
3D print energy	kWh	0.46	1.73	-	-
Pump use energy	kWh	96.06	94.08		
Aluminium	kg	-	-	5.07	1,980.00
Plastics	kg	-	-	3.12	9.90
Copper	kg	-	-	0.91	9.90
Steel	kg	-	-	-	3,148.20
Cast iron	kg	-	-	-	4,752.00

The inputs in the LCI were converted to LCEI using SimaPro 8.4 LCA software. The LCEI breakdown in terms of inputs has been presented in Table 13. F impeller has lower LCEI values compared to the N impeller. Electricity consumption was found to be the major contributor to all environmental impact assessments of F impeller, which accounted to 69.6% of GWP, 62.5% of eutrophication, 72% of land use, 68.2% of CED, 59.4% of human toxicity, 54.7% of freshwater aquatic eco-toxicity, 52.9% of marine aquatic eco-toxicity, and 73% of terrestrial eco-toxicity of the F impeller. The energy consumption resulted in higher environmental impacts mainly due to CO_2, SO_x, and NO_x emissions from combustion of black coal and natural gas, accounting to 84.5% of Western Australia's mix (Department of the Industry, Science, Energy and Resources, 2020). Material processing stage also contributed to 70.2% of water use, 17.1% of human toxicity, 22.5% of freshwater eco-toxicity, and 23.6% of marine eco-toxicity due to high water-intensive nature of carbon-nylon composite production and emission of plastics to aquatic ecosystems.

Table 13 The breakdown of LCEI values of impellers in terms of inputs

Impact category	*Unit*	*Total LCEI*		*Variance*	*Design*		*Processing*		*Production*		*Use*	
		F	*N*		*F*	*N*	*F*	*N*	*F*	*N*	*F*	*N*
GWP	kg CO_2	2.56E+00	1.83E+01	86%	5.1%	0.7%	7.3%	1.0%	18.0%	88.5%	69.6%	9.7%
Eutrophication	kg PO_4^{3-} eq.	1.12E–03	8.78E–03	87%	4.6%	0.6%	16.2%	1.7%	16.7%	89.7%	62.5%	7.9%
Land use	Ha. a	1.18E–05	6.77E–05	83%	5.3%	0.9%	5.2%	1.7%	17.6%	84.8%	72.0%	12.6%
Water use	M^3 H_2O	1.61E–02	1.31E–01	88%	1.3%	0.2%	70.2%	13.0%	10.3%	84.6%	18.2%	2.2%
CED	MJ	3.40E+01	2.36E+02	86%	5.0%	0.7%	9.3%	1.2%	17.6%	88.3%	68.2%	9.8%
Human toxicity	kg 1,4-DB eq.	2.02E–01	8.69E+00	98%	4.4%	0.1%	17.1%	0.2%	19.2%	98.3%	59.4%	1.4%
Fresh water eco-toxicity	kg 1,4-DB eq.	5.79E–02	2.65E+00	98%	4.0%	0.1%	22.5%	0.3%	18.8%	98.4%	54.7%	1.2%
Marine eco-toxicity	kg 1,4-DB eq.	1.98E+02	5.76E+03	97%	3.9%	0.1%	23.6%	0.5%	19.6%	97.6%	52.9%	1.8%
Terrestrial eco-toxicity	kg 1,4-DB eq.	3.16E–03	7.57E–02	96%	5.4%	0.2%	4.2%	0.2%	17.4%	96.5%	73.0%	3.0%
Acidification	kg SO_2 eq.	6.26E–03	5.97E–02	90%	4.7%	0.5%	12.6%	1.0%	18.0%	91.7%	64.7%	6.8%
ADP	kg Sb eq.	1.11E–06	1.64E–05	93%	0.1%	0.0%	7.2%	0.5%	90.9%	99.4%	1.8%	0.1%
Particulate matter	kg $PM_{2.5}$ eq.	7.44E–04	4.62E–03	84%	5.1%	0.8%	8.6%	1.4%	17.1%	86.7%	69.2%	11.1%
Photochemical smog	kg NMVOC eq.	8.33E–03	6.94E–02	88%	5.1%	0.6%	6.8%	0.7%	18.6%	90.3%	69.6%	8.3%

The production stage of N impeller showed the highest contribution for all environmental impacts. The inputs of material and energy consumption for aluminium and steel in the CNC machine has contributed to 78.1% of GWP, 80% of eutrophication, 70.5% of land use, 79.1% of water use, 72.2% of CED, 35.3% of human toxicity, 62.5% of freshwater aquatic eco-toxicity, 79.6% of marine aquatic eco-toxicity, and 81.4% of terrestrial eco-toxicity of the N impeller. The high carbon steel material used in cutting tools causes metal poisoning accounts for 61.7% of human toxicity, 34.7% of freshwater aquatic eco-toxicity, 16.1% of marine aquatic eco-toxicity, and 9.74% of terrestrial eco-toxicity of the N impeller. The use of coolant/lubricant fluid in subtractive manufacturing of N impeller has only contributed to 6.2% of CED due to reusability of coolant fluid. Further analysis of environmental impacts was done in EE after normalisation and weighting.

3.3 Life cycle costs

The PVs are first determined by the LCC of impellers. The PVs of the 3D printed F and N impellers are presented in Table 14. The calculated costs were adjusted for inflation and discounted to the PV.

Table 14 PV production

Year	*Capital cost (AUD)*		*Replacement cost (AUD)*				*Manufacturing cost (AUD)*	
	3D Printer	*CNC machine*	*Nozzle*	*Build plate*	*Coolant*	*Cutting tools*	*F*	*Nylon*
0	8,562	64,224						
1	-	-	157	-	335	476	9,824	63,995
2	-	-	225	-	319	453	9,355	60,945
3	-	-	214	214	304	432	8,909	58,040
4	-	-	204	-	290	411	8,485	55,274
5	-	-	194	-	276	392	8,080	52,639
6	6,387	-	123	185	263	373	7,695	50,130
7	-	-	176	-	250	355	7,328	47,741
8	-	-	168	-	238	338	6,979	45,465
9	-	-	160	160	227	322	6,646	43,298
10	-	-	152	-	216	307	6,330	41,235
Total	14,949	64,224	1,772	558	2,717	3,860	79,632	518,764

Table 15 shows the PI calculations of the impellers. A CRF of 0.142 was used to convert the $PV_{total,prod}$ to annuities and they were divided by POs of 549 (F) and 586 (N) to obtain the $LCC_{impeller,prod}$, which is then converted to the PI after incorporating a PM of 35%.

Table 15 Price of the impeller

	$PV_{total,prod.}$ *(AUD)*	*Annuitised cost (AUD)*	*PO*	$LCC_{impeller,prod}$ *(AUD)*	*PI(AUD)*
F	96911.5	13798	549	25.13	33.93
Nylon	589565.0	83941	586	143.24	193.38

Table 16 shows the PV pump usage costs considering PI as the capital cost and the cost of energy as the operating cost to achieve a constant pressure head of 35 kPa by each impeller. A similar impeller life of 200 hours 5 months as explained in the fatigue life section, was estimated for both impellers as per usage of 2 hours per day for 20 working days per month.

Table 16 PV pump usage

Month	*N impeller*		*F impeller*	
	Capital cost (AUD)	*O&M cost (AUD)*	*Capital cost (AUD)*	*O&M cost (AUD)*
0	193.38		33.93	
1		5.40		5.51
2		5.38		5.49
3		5.35		5.47
4		5.33		5.44
5		5.31		5.42
Total	193.38	26.77	33.93	27.34

Table 17 LCC pump usage

	$PV_{total,P}$ *(AUD)*	*Annuitised cost (AUD)*	$LCC_{P,SL}$ *(AUD)*
F	61.27	154.28	64.28
Nylon	220.15	554.39	231.00

The F impeller showed 82.5% lower production cost compared to N impeller due to lower capital costs (75.2%), lower replacement costs (62.2%) and lower manufacturing costs (83.6%). The manufacturing stage showed the highest cost values due to high labour costs (64.6% in N impeller and 41.1% in F impeller). Higher labour costs in N impeller were due to operator time required for multiple processes (2.24 h) of turning, drilling, and milling in subtractive manufacturing whereas, operator's time for the single process of 3D printing is only required during loading and the removal of the part (0.25 h) (3DEO, 2017). Even though nylon 6/6 is a cheaper material compared to composites, N impeller has higher cost values in the material processing stage (20.8%) due to materials wasted in subtractive manufacturing. The F impeller consumes less composite material (36.6%) due to additive nature of the manufacturing process resulting in lower material costs and losses. The operating cost of F impeller is higher than the N impeller due to the fact that the former consumes 2% more energy in pump usage than the latter due to lower pumping performance.

3.4 EE assessment

The EE assessment was conducted using the LCEI values from the LCA and the LCC values in order to calculate the portfolio positions for F and N impellers. The LCEI values were normalised and weighted using the normalisation factors and weights as listed in Table 2 [equations (10)–(11)]. Table 18 presents the normalised values of environmental impacts in terms of inhabitants. The EIs in terms of inhabitants allowed comparative assertions.

Table 18 Environmental impacts after normalisation

Indicator	*Weights (W_i)*	*EI_F*	*EI_N*
GWP	11.44%	1.02E–05	7.28E–05
Photochemical smog	9.06%	1.01E–05	8.39E–05
Particulate matter	10.42%	1.72E–06	1.07E–05
Eutrophication	9.51%	5.59E–06	4.39E–05
Eco-toxicity	10.08%	4.55E–05	1.96E–03
Land use	8.83%	4.02E–08	2.30E–07
Acidification potential	8.38%	4.26E–06	4.07E–05
ADP	9.85%	3.63E–10	5.37E–09
Water use	10.99%	1.90E–06	1.55E–05
CED	11.44%	1.58E–05	1.09E–04
Total		9.50E–05	2.34E–03

The total EI of 3D printed F impeller was found to be 96% lower than the subtractive manufactured N impeller. The eco-toxicity (48%) of F impeller was found to be the predominant impact with the highest contribution from freshwater eco-toxicity followed by CED (17%), photochemical smog (11%) and global warming potential (11%). This is due to the emissions from the use stage energy consumption and material processing of carbon-nylon composite. In comparison, the eco-toxicity (84%) of N impeller was found to be the highest impact followed by cumulative energy demand (5%), photochemical smog (4%) and global warming potential (3%). This is mainly due to the emissions from the use of energy and material intensive aluminium and emissions from steel made cutting tools used in the CNC machine during the manufacturing stage of N impeller. These higher impact values depend not only on the type of inputs used in the manufacturing process but also on the weighting factors given by the respondents in the consensus survey as indicated by weights in GWP (11.44%) and CED (11.44%).

The LCC values were normalised with the Australian GDP/Inh value of AUD 74,222/Inh [equation (12)]. Table 19 presents the normalised costs and normalised impacts of each impeller. The F impeller showed 71% lower NC compared to N impeller.

Table 19 Normalised costs and impacts of impellers

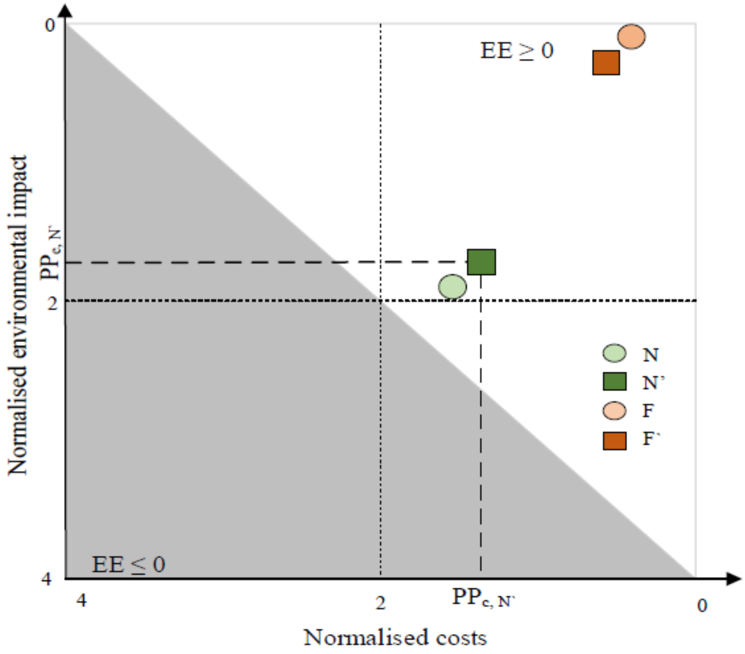
Configuration	*EI_n (inhabitants)*	*NC_n (inhabitants)*
N	2.34E–03	2.99E–03
F	9.50E–05	8.66E–04

The $R_{E/C}$ value was calculated as 0.631 according to equation (15) which shows that costs are more influential than the environmental impacts. The preliminary portfolio positions ($PP_{c,n}$, $PP_{e,n}$) and revised portfolio positions ($PP'_{c,n}$, $PP'_{e,n}$) (Table 20) determined from equations (15)–(17) were plotted on the EE portfolio as shown in Figure 19.

Table 20 Portfolio positions

Impeller	*PPe*	*PPc*	*PP'e*	*PP'c*
N	1.9219	1.5509	1.7323	1.4377
F	0.0781	0.4491	0.2677	0.5623

Figure 19 EE portfolio (see online version for colours)



In the revised portfolio, both N and F impellers exhibited positions above the diagonal line indicating positive EE. However, impeller F exhibited the highest EE while the impeller N showed comparatively lower EE.

The higher EE of pump impeller F was due to lower material consumption, lower energy consumption, lower labour costs, and lower environmental impacts as explored in ELCA and LCC. The lower EE of N impeller is due to higher material consumption, higher energy consumption, higher labour costs, use of cutting/lubricating fluids, and cutting tools in conventional subtractive manufacturing causing higher environmental impacts as explored in ELCA and LCC. The purpose of the revised EE portfolio is to determine the most eco-efficient option, which is the 3D printed fibreglass reinforced Onyx (F) impeller.

The EE of the F impeller can be further improved by considering cause-diagnosis and improvement strategies iteratively using follow up LCAs. The virgin carbon-nylon composite contributes to the high eco-toxicity (48%) and material costs (36.6%) of F impeller. Therefore, EE of F impeller can be further improved by replacing virgin material with recycled materials as it avoids further upstream processes and the associated environmental impacts. However, it warrants investigation into the technical feasibility of recycled material before considering EE analysis. EE of F impeller can also be improved by optimising the 3D printing process parameters such as reinforcement materials and reinforcement levels. EE improvement by optimising the design for material conservation was not explored in this study due to the geometry of the pump impeller.

4 Conclusions and recommendations

This study developed a TEE framework and evaluated the TEE performance of 3D printed pump impellers manufactured using FFF of composite materials. The technical performance evaluation determined the feasibility of 3D printed parts for a specific application whereas the ELCA and LCC evaluations determine the EE of the impellers. The TEE framework differentiates from other LCA methods by presenting a comprehensive evaluation incorporating technical feasibility into EE. The EE portfolio further allows the reduction of environmental impacts whilst not entailing excessive costs to achieve sustainable 3D printing.

The results of the technical feasibility assessment identified that all impellers have acceptable surface roughness and dimensional tolerances whilst only the F (fibre-reinforced) impeller exhibited feasible technical performance and the C (solid infill), T (50% triangular infill), and H (50% hexagonal infill) impellers showed lower tensile and fatigue properties compared to conventional nylon 6/6 benchmark. Therefore, 3D printed parts with different configurations except impeller F were not considered in EE analysis.

The total EI of 3D printed F impeller was found to be 96% lower than the subtractive manufactured N impeller. The F impeller showed 71% lower NC compared to N impeller. Thus, the EE analysis identified that both N and F impellers showed EE ≥ 0, while F impeller showed comparatively higher EE. This qualifies fibreglass reinforced 3D printed impeller (F) as a techno-eco-efficient product. The TEE framework supports the selection of technically feasible, economically viable, and environmentally benign sustainable manufacturing strategies. The application of 3D printed pump impellers validates the application of the TEE framework and proved 3D printing as a sustainable manufacturing strategy.

3D printing could pose social implications such as the change in labour structure due to automation, improved health and safety conditions, shorter supply chains, job creation through localised or more decentralised production. These social implications associated with 3D printing will be further investigated in the future work.

In the EE portfolio, causes for impellers not being eco-efficient can be identified using hotspot analysis. The processes or inputs in the eco-inefficient impeller life cycle contributing to the higher environmental and economic impacts, and lower technical performance, can be diagnosed so that relevant strategies can be implemented in order to mitigate the negative outcomes (Arceo et al., 2018). Current research on the influence of technical performance plays a pivotal role in improving EE performance. Recommendations and applications of EE strategies could be applied to eco-inefficient impellers to reduce life cycle emissions, and resource consumption in order to improve the end-of-life product recovery, and finally to enhance durability, and SL.

When incorporating EE improving strategies, life cycle stages and inputs may be altered and would require updating LCI. Accordingly, follow up ELCA and LCC would need to be conducted to obtain the revised portfolio positions of these impellers. Revised ELCA and LCC values may or may not improve the EE portfolio positions of the impellers. EE strategies of alternative materials, process optimisation, and design optimisation can cause significant changes in environmental impact and incremental costs, but it may still not allow the impeller portfolio positions to go above the diagonal line. Therefore, it involves an iterative process using alternative EE strategies until EE ≥ 0.

Further research could also be conducted to determine the TEE performance of different reinforcement materials, metal 3D printed parts, and compare the results with conventional subtractive manufactured counterparts. Furthermore, technical performance could be evaluated with computer numerical simulations and non-destructive testing methods. This could support the transition of manufacturing from conventional methods to 3D printing in the future. The emerging 3D printing technologies could further simplify the manufacturing landscape and manufacturing industry decision-makers should be aware of the TEE potential of 3D printing.

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Abbreviations

CMM	Coordinate measuring machine
CNC	Computer numerically controlled
CED	Cumulative energy demand
EE	Eco-efficiency
EI	Environmental impact
ELCA	Environmental life cycle assessment
eq.	Equivalent
FFF	Fused filament fabrication
FU	Functional unit
GDEI	Gross domestic environmental impact
GDP	Gross domestic production
GWP	Global warming potential
H	Head
LCC	Life cycle costing
LCEI	Life cycle environmental impact
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
NEI	Normalised environmental impact
NC	Normalised cost
NPV	Net present value
PP	Portfolio position
$\dot{Q}$	Flow rate
UTS	Ultimate tensile stress

APPENDIX C – ARTICLE 3

Jayawardane, H., I. Davies, J. R. Gamage, M. John, and W. Biswas. (2022). "Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining." *The International Journal of Advanced Manufacturing Technology*, 121, 6811–6836. DOI: 10.1007/s00170-022-09748-2.

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Authorship agreement

I, Heshan Thenuka Wijerathne Jayawardane, contributed 80% to the paper entitled 'Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining'.

Mr. H.T.W. Jayawardane

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Author	Signature
Ian J. Davies	
J. R. Gamage	
Michele John	
Wahidul K. Biswas	

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ORIGINAL ARTICLE

Investigating the 'techno-eco-efficiency' performance of pump impellers: metal 3D printing vs. CNC machining

Heshan Jayawardane[1] · **Ian J. Davies**[2] · **J. R. Gamage**[3] · **Michele John**[1] · **Wahidul K. Biswas**[1]

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Abstract

The economic, environmental, and social impacts caused by the extensive resource consumption and harmful emissions from the metal manufacturing industry should be lowered through innovative sustainable manufacturing strategies. This study aims to investigate the techno-eco-efficiency performance of metal 3D-printed parts in comparison with CNC-machined parts to determine the technical, economic, and environmental performance as a decision support tool for selecting the most techno-eco-efficient manufacturing method. In this study, a novel metal extrusion 3D printing technology has been used to create a centrifugal semi-open pump impeller in 316L stainless steel material. The technical feasibility of the impellers has been determined by evaluating the geometry, build material, mechanics, morphology, and functional performance of the impellers. The eco-efficiency performance of technically feasible impellers was evaluated through environmental life cycle assessment, life cycle costing, and portfolio analysis. This eco-efficiency analysis helped ascertain the cost-competitiveness and environmentally friendliness of the 3D-printed impellers by comparing it with the conventional impellers. The findings reveal that the AM impeller is eco-efficient mainly due to lower normalised environmental impacts (54.6%) compared to the SM impeller. The functional parts made by metal extrusion 3D printing are technically feasible, cost-effective, and environmentally friendly compared to the SM counterparts.

Keywords Metal additive manufacturing · Sustainable manufacturing · Bound metal deposition · Metal extrusion · Life cycle assessment · Techno-eco-efficiency

Abbreviations

AM	Additive manufacturing
BMD	Bound metal deposition
CED	Cumulative energy demand
CMM	Coordinate measuring machine
CNC	Computer numerical control
DED	Directed energy deposition
EEA	Eco-efficiency assessment
EI	Environmental impact
ELCA	Environmental life cycle assessment
Eq.	Equivalent
FU	Functional unit
GDEI	Gross domestic environmental impact
GDP	Gross domestic product
GWP	Global warming potential
LCC	Life cycle costing
LCEI	Life cycle environmental impact
LCI	Life cycle inventory
Nei	Normalised environmental impact
NC	Normalised cost
NPV	Net present value
PBF	Powder bed fusion
PP	Portfolio position
UTS	Ultimate tensile stress

✉ Heshan Jayawardane
h.wijerath@postgrad.curtin.edu.au

Ian J. Davies
i.davies@curtin.edu.au

J. R. Gamage
gamagejr@uom.lk

Michele John
m.rosano@curtin.edu.au

Wahidul K. Biswas
w.biswas@curtin.edu.au

[1] Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

[2] School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

[3] Department of Mechanical Engineering, University of Moratuwa, Moratuwa, Sri Lanka

1 Introduction

The manufacturing value addition contributes 16.0% to global gross domestic product (GDP) [1] and accounts for significant portions of the total global energy consumption and environmental emissions. The main energy sources that support industrial energy consumption are oil (31.6%), coal (26.9%), and natural gas (22.8%) [2]. The manufacturing sector's energy use accounts for 24.2% of global greenhouse gas emissions, despite significant efforts to limit atmospheric emissions, solid waste, and effluents [3]. The manufacturing of metallic products is one of the main contributors to the environmental footprint of an industrial production system resulting mainly from the use of various metalworking processes and resource-intensive technologies [4]. The mining, material processing, manufacturing, usage, and disposal activities during the life cycle of metallic products cause significant emissions, waste, and resource depletion compared to non-metallic products [5]. Primary metal manufacturing alone accounts for 32.5% of the global coal energy consumption [2], and 16.9% of total energy consumption in Australia [6]. The industrial production of iron and steel accounts for 7.2% of global greenhouse gas emissions [3]. The extensive resource consumption and harmful emissions from the primary metal manufacturing industry should be lowered by applying innovative sustainable manufacturing strategies.

The manufacturing industry heavily relies on subtractive manufacturing (SM) technologies due to significant product quality gained by retaining the bulk material properties [7]. However, SM is resource inefficient as the material needs to be removed from the work blank using cutting tools to achieve the desired shape of the product [8]. Furthermore, these subtractive systems can only manufacture designs that cutting tools can reach, making them unable to produce complex metal parts [9]. The machining waste including machining lubricants, eventually end up in landfills, where they cause eco-toxicity [10]. The computer numerical control (CNC) machining approach using 3D model data has improved the efficiency of SM and minimised wastage while maintaining consistent product quality. Although the energy efficiency, cutting fluid control, and multi-axis operation of CNC machining have been constantly improved [11], waste generation cannot be totally eliminated.

Additive manufacturing (AM) or 3D printing is a cutting-edge manufacturing technique that can create functional components from polymers, ceramics, metals, composites, and biomaterials [12]. Metal AM methods include powder bed fusion (PBF), directed energy deposition (DED), binder jetting, metal material extrusion, and ultrasonic AM, depending on the manufacturing technology. The most common PBF AM technologies are selective laser melting (SLM) and electron beam melting (EBM), while the most common DED AM technologies are laser engineered net shaping (LENS), directed metal deposition (DMD), and electron beam additive manufacturing (EBAM) [13, 14]. Metal AM could be a promising alternative manufacturing option that may potentially address the aforementioned weaknesses associated with the use of SM for metallic components. Firstly, metal AM has the ability to produce complex, functional, high-value parts in a short lead time due to the elimination of tools, fixtures, and jigs used in SM [15]. Secondly, metal AM could reduce material wastage during the manufacturing process due to its additive nature [16]. Finally, metal AM could allow the fabrication of generative designs, simplifying the design stage costs [17]. However, AM possess several limitations such as limited material availability, high production time, high production cost, lower surface quality, residual stresses, and deformation of parts [18].

Metal AM methods such as SLM and EBM have the inherent drawbacks of high-energy consumption (31 kWh/kg for 316L stainless steel in SLM), high cost of metallic powder, toxicity of metallic powder, and its inability to make hollow parts due to the use of laser beams and electron beams as a primary energy source [19, 20]. Metal extrusion AM is a novel technology which addresses the limitations of conventional powder-based metal AM [21]. In several studies, metals have been mixed with polymers such as polylactic acid (PLA), resulting in higher technical properties than virgin polymers [22]. Furthermore, metals have also been mixed with ceramic clay to develop cermet materials. These materials could be extruded through piston or screw injectors for metal extrusion AM [17]. *Desktop Metal* and *Markforged* have commercialised this metal extrusion AM technology to produce functional metallic components for industrial, medical, aeronautical, and space applications [23, 24].

Desktop Metal's bound metal deposition (BMD) technology utilises conventional metal injection moulding principles to produce high-quality metal parts without incurring high production costs. This novel technology allows metal, bound within a ceramic binder to be extruded according to a 3D model. The obtained green part then needs to be debinded to remove the primary binder from the metal part through solvent decomposition. Then, the porous metal part is sintered in a furnace until the required metal density (96–99%) is obtained [23]. Post-processing methods such as polishing, sandblasting, heat treatment, and hot isostatic pressing have been used to improve surface properties, technical properties, and residual porosity of metal AM parts [25].

Since metal extrusion AM is relatively new, technical feasibility of the technology is still limited. Several studies, however, have quantified the mechanical properties of metal 3D-printed parts from BMD technology [17, 26]. Thompson et al. [17] have stated that the density, dimensional measurement for shrinkage, and flexural strength of the 316L stainless steel specimens made by BMD is similar to rolled sheet metal bulk material. The findings also showed that BMD enables small-scale production of bespoke metal parts at a lower cost and reduced time, compared to conventional SM. Sadaf et al. [26] stated that 316L stainless steel specimens made by BMD exhibited a yield point of 250 MPa, a tensile strength of 520 MPa, and a Vickers microhardness of 285 HV, which is similar to the technical properties of conventional annealed steel. Jiang and Ning [25] have investigated the tensile and flexural fatigue properties of 316L stainless steel made through BMD, which has also shown feasible technical results compared to bulk material properties. All these studies have focused on the use of 316L stainless steel in metal AM and have evaluated its technical performance. However, it is also important to assess the performance of 3D-printed products during the use stage to investigate if AM has any effect on product's durability, as it could also change the economic and environmental impacts.

Stringent environmental regulations, increased environmental consciousness among the general public, and competitive markets have pushed manufacturers to consider cleaner production strategies to reduce the environmental footprint of manufacturing activities [7]. The environmental life cycle assessment (ELCA) has been the most effective tool for evaluating environmental impact [27]. Due to the novelty of BMD, there are no studies that evaluate the environmental impacts of BMD metal AM products. However, extensive studies have been conducted to evaluate the environmental performance of other metal AM technologies. Faludi et al. [19] have studied the environmental impact of aluminium in selective laser melting. The results showed that the cumulative energy demand during the manufacturing stage was the most dominant impact in the analysis while embodied energy per unit decreased with higher utilisation of the build envelope. Baumers et al. [20] have also studied the environmental impact of electron beam melting using the power consumption of metal AM under different build volume utilisation scenarios. Peng et al. [7] have studied the environmental impact of AM and SM under the indicators of global warming potential (GWP), acidification potential (AP), abiotic depletion potential (ADP), eutrophication potential (EP), and respiratory inorganics (RI) using the ELCA method. The results show that indicators of pure AM products are approximately twice that of SM products, mainly due to the high energy consumption and use of toxic metal powder.

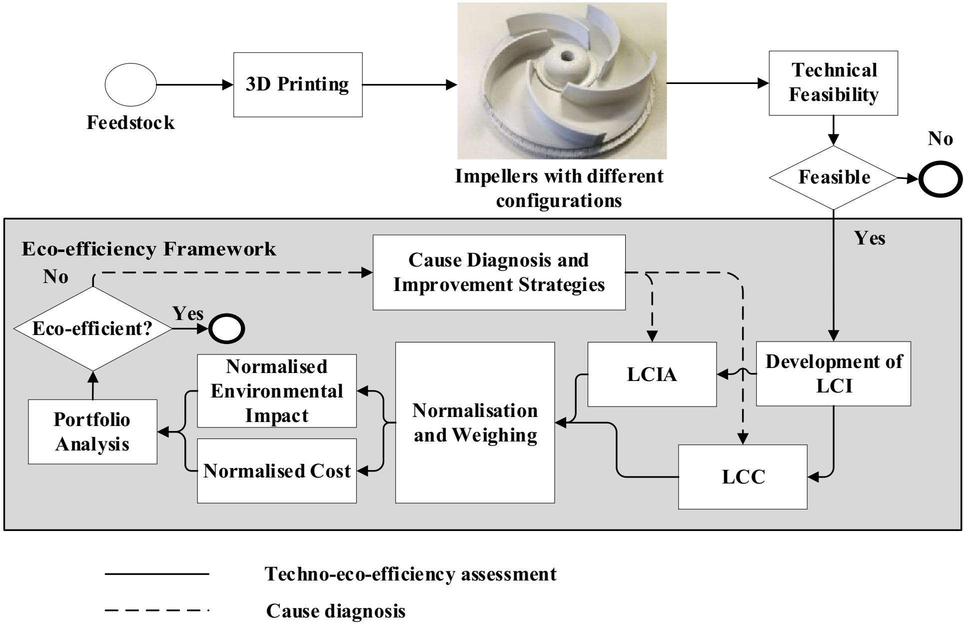
The economic impact of manufacturing systems has predominantly been studied using life cycle costing (LCC) assessments [28, 29]. Studies have been conducted to evaluate the costs associated with BMD metal AM using LCC models. Watson et al. [30] stated that BMD technology has lowered the capital and operational costs of metal AM by 60–80% in comparison to PBF and DED. However, the study has not determined whether the benefit of cost reduction has occurred by reducing the technical performance of the 3D-printed products. Furthermore, there appear to have been no studies to date that determine the economic and environmental implications of the 3D printed products made from metal extrusion AM technology. Therefore, it warrants an investigation into whether functional metal AM parts can deliver reduced levels of environmental impact in a cost-competitive manner. In order to address this research question, a techno-eco-efficiency framework can be considered. Jayawardane et al. [31] developed this framework specifically for sustainable manufacturing research to evaluate the eco-efficiency performance of technically feasible parts through environmental life cycle assessment (ELCA), life cycle costing (LCC), and portfolio analyses. This study was conducted to evaluate the techno-eco-efficiency of polymer composite material made through fused filament fabrication. The same framework could be used to determine the technical feasibility and eco-efficiency performance of 316L stainless steel pump impellers through various assessments.

This study aims to investigate the techno-eco-efficiency performance of metal AM parts in comparison with metal SM parts to determine the technical, economic, and environmental performance of metal AM, as a decision support tool to select the most techno-eco-efficient manufacturing method for the selected part. The paper only focuses on the use of virgin material in a novel metal AM technology as the durability and mechanical performance of 3D-printed products are still unknown. Firstly, a technical feasibility assessment of AM specimens and parts has been conducted to investigate the influence of AM on durability of parts in the use stage of the given application. Following this, the study evaluated the economic and environmental impacts of metal AM parts compared to SM parts through a combination of ELCA and LCC for the eco-efficiency (EE) analysis to determine the techno-eco-efficient method for manufacturing the parts.

2 Materials and method

The techno-eco-efficiency framework (Fig. 1) developed by Jayawardane et al. [31] has been used in this study to evaluate the techno-eco-efficiency performance of manufactured parts. Firstly, the material feedstock will be used to 3D print the metallic components following the parametric configurations. Secondly, the technical feasibility of the 3D printed product will be evaluated by benchmarking

Fig. 1 Theoretical framework [31]



with CNC-machined counterparts, including their geometric properties, surface properties, mechanical properties, build material properties, and functional performance. The ELCA and LCC will be analysed and will be utilised in the eco-efficiency framework to determine the eco-efficiency performance of metal AM products and CNC-machined counterparts for comparative assessment.

Inputs (energy, material, utility, labour, and transport) and outputs (solid waste and emissions to air, water, and soil) during the life cycle stages, including material processing, manufacturing, and use of metal AM parts and SM parts were incorporated into the life cycle inventory (LCI). The SimaPro software has been used for the first stage of the ELCA, the life cycle impact assessment (LCIA) by converting the LCI into the relevant life cycle environmental impacts (LCEI) depending on the indicators selected through an expert survey. Alternatively, relevant cost values for corresponding inputs of LCI are used to estimate the LCC. The LCEI and LCC have been then normalised by dividing with relevant normalisation factors; LCEI with gross domestic environmental impact per inhabitant (GDEI/Inh) and LCC with gross domestic product per inhabitant (GDP/Inh). The normalised environmental impacts (NEI) are then weighted by multiplying them by the corresponding weighting factors. The final normalised values are used in the eco-efficiency portfolio analysis to determine the eco-efficiency of technically feasible parts through a comparative analysis. This framework developed by Jayawardane et al. [31] has been implemented to determine the techno-eco-efficiency of metal 3D printed parts.

2.1 Part selection

The same parts selection procedure adopted by Jayawardane et al. [31] has been followed in this research study. A centrifugal semi-open pump impeller has been selected as the most feasible product from a product portfolio (closed centrifugal pump impeller, semi-open centrifugal pump impeller, and spur gear). A feasibility score has been given to each product in terms of complexity, solid-to-envelope ratio, application, functionality, and availability of performance testing criteria. The semi-open centrifugal pump impeller has been selected with the highest feasibility score in this multi-criteria decision-making model [31]. The impeller is complex and comparatively difficult to manufacture by AM and SM methods. The impeller also has a high solid-to-envelope ratio, which makes it costly to manufacture using conventional SM methods. The impeller has also been scored on the availability of standard performance testing criteria for the functional application of a submersible wastewater pump (*Grundfos Unilift KP-250*) capable of pumping industrial and domestic effluents with particles up to 10 mm [32].

2.2 Manufacturing of pump impellers

A *Desktop Metal* Studio facility at Curtin University's John de Laeter Research Centre (JdLC) was utilised for metal additive manufacturing, while CNC machines (lathe, mill, drill) from the same university's manufacturing laboratory was used for conventional subtractive manufacturing. The 316L stainless steel material was selected from a *Desktop*

Metal material portfolio of 17–4 PH stainless steel, including 316L stainless steel, H13 tool steel, 4140 mild steel, and copper, because it is similar to the 304 stainless steel material used in the OEM pump impeller. The 316L stainless steel material has higher mechanical properties for a wide range of temperatures and possesses excellent corrosion resistance, thereby making it suitable for use in impellers under harsh environments. *Desktop Metal* 316L stainless steel material rods were used for metal 3D printing, and 316L stainless steel bulk material in billet form was used for CNC machining. Three impellers (AM1, AM2, AM3) were additive manufactured while three impellers (SM1, SM2, SM3) were subtractive manufactured.

2.2.1 Metal additive manufacturing

The centrifugal pump impeller (Fig. 2a and b) was 3D printed from 316L stainless steel by the *Desktop Metal* Studio 3D printer (Fig. 2c) using the BMD Technology.

The following configuration and parameters were used in 3D printing the pump impeller (Table 1). The 3D-printed 'green parts' were lightly cleaned with a brush to remove any scrap material and then debinded in the *Desktop Metal* debinder to remove the primary binder material. The debinded 'brown parts' were sintered to remove the residual binder and to solidify the final part.

2.2.2 Metal CNC machining

The impeller blade profiles for metal CNC machining were generated from the 3D model of the pump impeller using the *SolidWorks*® software. The benchmark pump impeller (Fig. 3a and b) was made from 316L stainless steel bulk material by subtractive manufacturing. The work blank for the impeller was a 316L stainless steel cylinder with a diameter of 100 mm. A *Leadwell* CNC lathe was used for turning the stainless steel work blank to the required diameter. The work blank was then machined using a *Leadwell V30* CNC milling machine (Fig. 3c) to manufacture the impeller blade profile. The coupling hole in the shape of the shaft profile of the pump was made using a *FANUC Robocut* wire electrode discharge machine (EDM). Finally, the impeller collar was CNC machined using the Leadwell V30 CNC milling machine separately and was spot welded to the impeller due to the difficulty in machining the impeller collar profile with the impeller vanes.

Table 1 Material and part configuration for 3D-printed impeller

Parameter	Configuration
Material	316L stainless steel
Material profile	Standard + profile
Extruder diameter	0.4 mm
Infill density (%)	100
Infill pattern	Solid (square cross-hath spacing)
Print speed	30.00 mm/s
Roof and floor thickness	1.80 mm
Roof and floor layers	24
Wall thickness	1.44 mm
Walls layers	3
Layer height	0.15 mm
Nozzle diameter	0.40 mm
Orientation/Raster angle	*XY*/0°
Printing temperature	175 °C
Build plate temperature	65 °C
Debinding temperature	250–350 °C
Sintering temperature	900–1250 °C
Sintering scale factor (*x*, *y*, *z*)	1.16

Table 2 shows the configuration and parameters of the machines used for the subtractive manufacturing of the benchmark pump impeller.

2.3 Technical feasibility assessment

Prior to the assessment of economic and environmental performance, technical performance should be evaluated. The following properties have been selected to be evaluated in the technical performance assessment.

2.3.1 Density

Porosity is an important consideration in metal 3D printing since it affects the mechanical response by acting as a null strength dispersed phase in a two-phase composite [26]. As a non-destructive method, product density has become

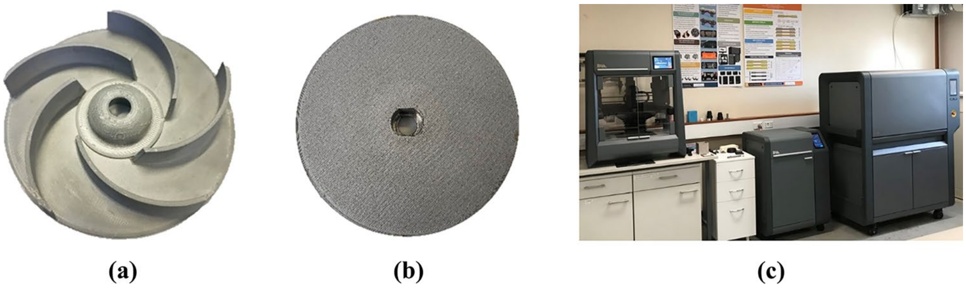


Fig. 2 3D printed pump impeller—front (**a**), 3D-printed pump impeller—rear (**b**), and *Desktop Metal* Studio in JDLC, Curtin University (**c**)

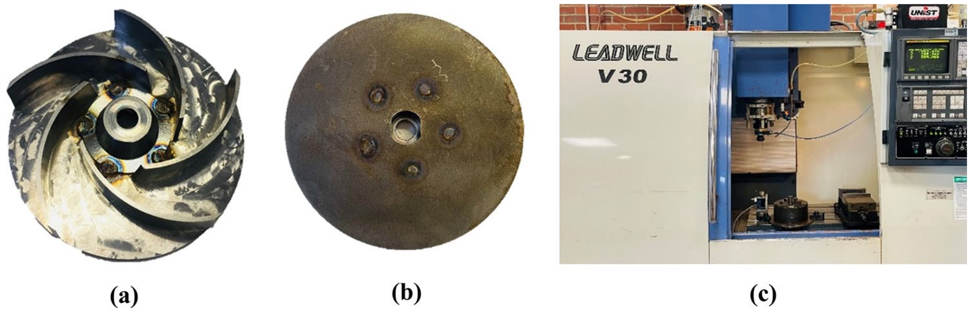


Fig. 3 SM pump impeller - front (**a**), SM pump impeller - rear (**b**), and *Leadwell V30* CNC milling machine (**c**)

an important measurement to determine the level of porosity of a component. Hence, the mean product density was determined following the ASTM D792/ISO 1183 standard method A. The mean density of the metal 3D printed impellers has been compared with the mean density of the CNC machined impellers in order to determine to test the effect of porosity in metal AM.

2.3.2 Surface roughness

The hydraulic and frictional losses within the pump can vary with the impeller's mean surface roughness (R_a) by changing the flow properties [31]. Therefore, a *Mitutoyo SJ-201* profilometer was used to measure the mean surface roughness of shrouds and vanes of the 3D-printed impellers (AM1, AM2, and AM3). The surface roughness of the AM impellers was benchmarked with the results of the SM impellers (SM1, SM2, and SM3).

2.3.3 Dimensional tolerance

The accurate measurement of dimensional tolerance of the pump impeller ensures fitting and clearance within the pump assembly. Peng et al. [7] state that the loose tolerance in the internal diameter of the impeller can cause improper fit and vibration between the impeller and pump shaft, resulting in impeller failure. Furthermore, tolerance of the outer diameter would affect the clearance between the impeller and pump housing. Therefore, dimensional measurements of the inner diameter (1), outer diameter (2), shroud thickness (3), and vane thickness (4) of the impeller (Fig. 4) were conducted using a *Sheffield Discovery II* coordinate measuring machine (CMM). The tolerances for OEM impeller were considered for comparison and benchmarking.

Table 2 Material and part configuration for CNC-machined impeller

Parameter	Configuration
Material	316L stainless steel
Machine 1	Leadwell CNC lathe
Machine 1 feed rate	96.60 m/min
Machine 2	Leadwell V30 vertical mill
Machine 2 feed rate	80.00 m/min
Machine 3	FANUC Robocut Wire EDM
Cutting tool	8.00 mm 3F EC high-speed steel
Depth of cut	0.20 mm
Width of cut	4.00 mm
Cutting fluid	ROCOL®

2.3.4 Geometric tolerance

The geometric tolerance measurement was conducted by 3D scanning the manufactured pump impellers using an *Artec Spyder* 3D scanner. The scanned model was aligned with the CAD model of the pump impeller by superimposition with specific alignment points at the vane surface. A distance map between the scanned model and the 3D CAD model was used to determine the degree of geometric deviation of the product features.

2.3.5 Tensile properties

The tensile properties which were deemed important for the mechanical performance of the impeller are ultimate tensile stress, percentage elongation, yield stress, and elastic modulus. Tensile strength indicates the material's response to withstand deformation due to tensile stresses. The impeller with higher tensile strength is more durable and offers longer service life due to higher fatigue properties. A uniaxial tensile test allows the measurement of these parameters. Six tensile test samples were manufactured and tested following the ASTM E8M standard to derive a stress–strain curve of the 3D printed 316L stainless steel material (AM1, AM2, AM3) and the 316L stainless steel bulk material (SM1, SM2, SM3) using a *Shimadzu Autograph* universal testing machine. The 3D-printed samples were printed in *XY*-orientation (along the build plate plane) with a 0° raster angle similar to the pump impellers. A load cell of 100 kN and a 5-mm/min crosshead speed was used in the tensile test to calculate the yield stress, ultimate tensile stress, percentage elongation, and elastic modulus along the *XY*-plane of the specimens.

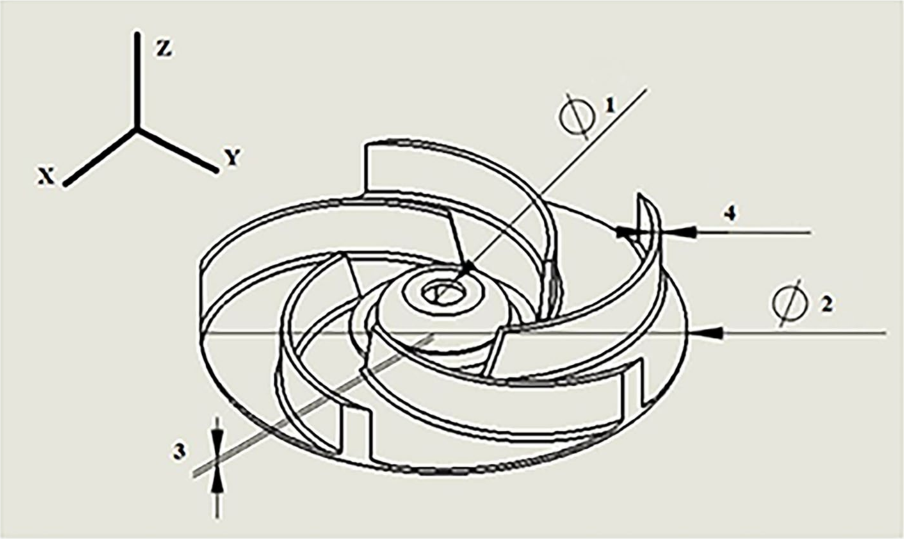


Fig. 4 Measured dimensions and orientation of the impeller

2.3.6 Fatigue properties

Fatigue properties such as fatigue strength and the number of cycles to failure are important in determining the service life of a component under cyclic loading conditions. A fatigue test determines the number of cycles to failure of a material at a specific stress level. The stress level at which the material withstands failure at a fatigue limit (10^6 cycles) is known as the fatigue strength. Materials failing at a higher number of fatigue cycles are more durable and possess an increased service life. The eco-efficiency performance could be potentially improved due to increased service life, which is an important consideration in the sustainability as it could help select the impeller with increased lifetime and resulting resource efficiency. A low cycle fatigue test was conducted with a reversed cycled rotating bending fatigue testing machine (Schenck-type) according to ISO 22407:2021. The fatigue test was displacement controlled with no deliberate stress concentrations. Nine test samples were tested for the number of cycles to failure at three different stress levels (90% of UTS, 80% of UTS, and 70% of UTS, which are above the material yield strength) for each manufacturing method.

The Basquin model equation (Eq. (1)) was used to model the *S–N* curves for the fatigue results of materials. The constants of the equation *(A, B)* were determined by substituting the applied cyclic tensile stress (S) and the number of cycles to failure (N) values for each stress level [33]. The fatigue life of an impeller was determined from the number of cycles to failure and pump speed (Eq. (2)).

$$S = A \times N^B \tag{1}$$

$$\text{Estimated fatigue life } (h) = N/\text{pump speed (cycles}/h) \tag{2}$$

2.3.7 Surface properties

The morphology of the 3D-printed surface and the fracture surface of the tensile specimens were used to explain the variations of technical properties of specimens. Pertuz et al. [33] stated that the defects and porosity within the specimen affect the technical performance. Therefore, the fracture morphology was observed using an Olympus BX51 light microscope. However, the voids and defects in specimens could not be quantified. The images were processed using the *ImageJ* software.

2.3.8 Hydraulic properties

The performance of the impeller in the functional application was determined by the ISO 9906 [34] standard for measuring hydraulic performance following the study of Jayawardane et al. [31]. The pump with different impellers was fitted to a pump test rig (Fig. 5). The water level at the suction point was used to calculate the static suction head (H_s) (Eq. (3)). The head at the discharge point ($H_{d,n}$) for each impeller (n) was measured by a pressure gauge. The pump head ($H_{\text{pump},\ n}$) was calculated by the difference of pressure heads (Eq. (4)) assuming no head loss (h—suction height, ρ_w—density of water, g—acceleration due to gravity). A flowmeter and a stopwatch were used to calculate the flow rate.

$$H_s = h \times \rho_w \times g \tag{3}$$

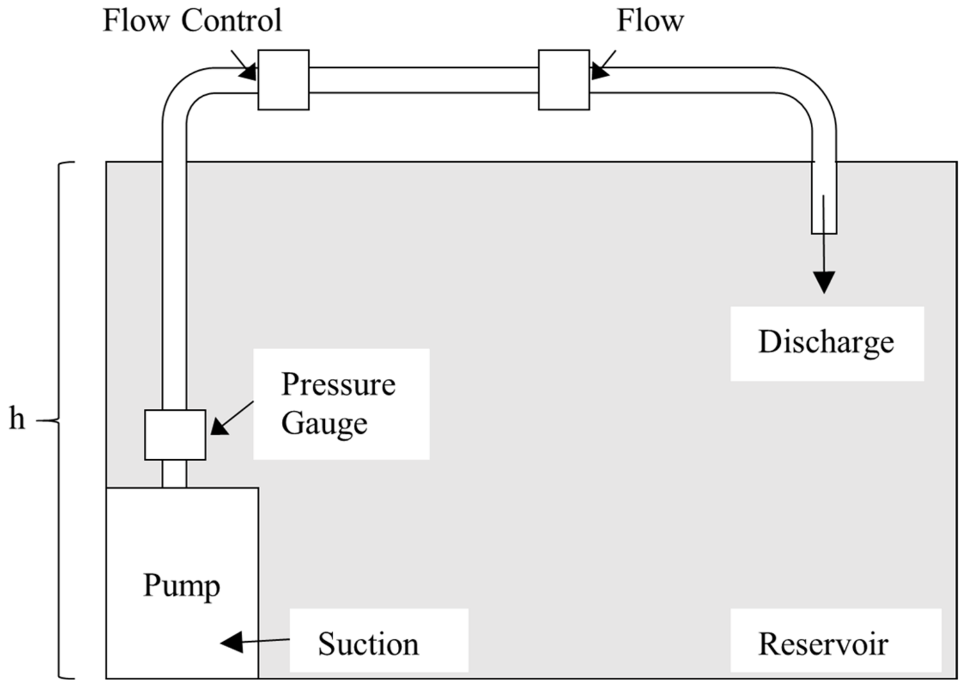


Fig. 5 Test rig for hydraulic performance [31]

$$H_{\mathrm{pump},n} = H_{d,n} - H_s \tag{4}$$

The values of head (H) and flow rate (Q) obtained from the hydraulic performance test were used to draw the performance curves to determine the energy consumption of impellers manufactured by metal AM and CNC machining. The hydraulic performance of the original equipment manufacturer (OEM) pump impeller (304 stainless steel) was used to compare the hydraulic performance of AM and CNC manufactured impellers.

2.4 Environmental life cycle assessment (ELCA)

Only the metal AM impellers that were found technically feasible were considered for sustainability assessment. The environmental impacts were determined using an environmental life cycle assessment (ELCA) following the ISO 14040–44 standard [35]. The functional unit (FU), which is needed for conducting a mass balance to determine the inputs and outputs used during the life cycle of an impeller, was chosen as *'the delivery of fluid by an impeller over its service life*'. All life cycle stages from 'design to use' were included in the scope of ELCA, as shown in Fig. 6. The inputs and outputs of the life cycle stages, including energy, materials, utility, labour, waste, and emission, were used to develop an LCI. The finishing machining operations for the metal AM impeller have also been accounted in the manufacturing stage. The service life of each impeller was considered as the timeframe of the use stage. A similar LCI and scope has been used for the benchmark SM impeller. The end-of-life stage of the impeller, which could be either recovery or disposal of the pump impeller was not considered, as this study concerns the feasibility of the metal AM products.

The environmental impacts of each impeller have been calculated by the SimaPro LCA software [36]. The authors only used the environmental impact indicator values, which have been considered as relevant to the Australian manufacturing industry. Thirteen environmental impacts were selected through a consensus survey involving the Australian manufacturing experts [31]. Global warming potential (GWP), eutrophication, land use, water use, and cumulative energy demand (CED) were the only indicators that could be calculated using the Australian indicator method. Therefore, EPD (2013) V1.02 method was used to calculate acidification potential and abiotic depletion potential (ADP), ILCD 2011 Midpoint + V1.08 method was used to calculate photochemical smog and particulate matter, and eco-toxicity was calculated using the CML-IA baseline V3.03 method.

2.5 Life cycle costing (LCC)

The life cycle costing analysis was conducted to determine the economic impacts of metal AM and CNC machined impellers following the ELCA. Following the LCC framework of Jayawardane et al. [31], the goal, scope, system boundary and LCI of both ELCA and LCC were the same and their outputs have the same denominator, which allows the integration of ELCA and LCC outputs to determine the EE portfolios of alternative options for comparative

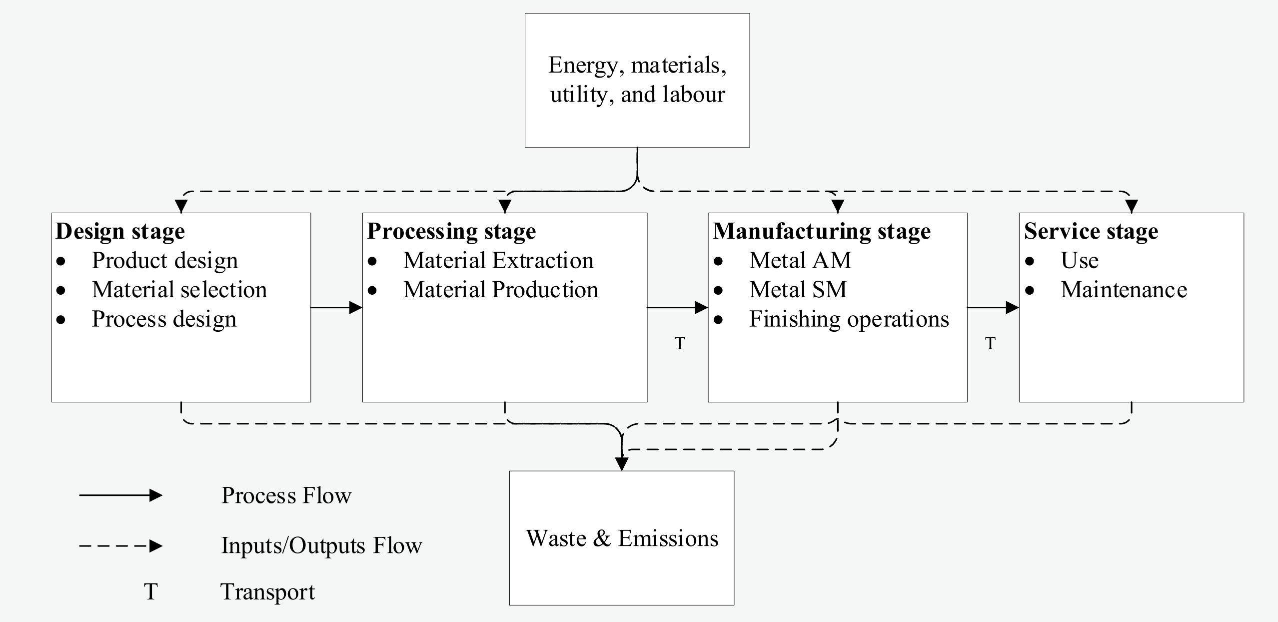


Fig. 6 The scope of ELCA [31]

purposes. The LCC was conducted to calculate the cost of *delivery of fluid during the service life of the impeller*. According to the AS/NZS 4536:1999 Australian/New Zealand Standard for life cycle costing—application guide [37], the LCC was calculated. The Microsoft Excel software was used to convert the LCI inputs to corresponding cost values obtained through a market survey. Only the labour costs which were included in the LCI were added to the cost items. The cost model was calculated in two steps: LCC of impeller production to calculate the unit cost of impellers, which was used as an input to the LCC of pumping operation. The end-of-life recovery or disposal costs were not incorporated in line with the scope of the ELCA. The LCC was performed in two steps:

Step 1: Capital costs, labour costs, energy costs, operations and maintenance costs, and transportation costs (Eq. (5)) from the design stage to the manufacturing stage were used to calculate the production cost of the impellers. The design stage costs include product design, process design, selection of material, and other utility costs [38]. The material processing costs included the raw material costs [23] and transportation costs from Massachusetts, USA to the metal 3D-printing facility in Perth, Australia [39]. The manufacturing stage overhead costs include the energy usage costs [40], equipment costs [23], and labour costs [41], which were apportioned to the manufacturing time for each impeller. A mass production of impellers was assumed for both the AM and SM over an equipment lifetime of 10 years (Eq. (5)). An inflation rate of 1.90% [42] and a discounting factor of 7% [43] were used in the LCC calculation. The sum of the present values (PV) of the costs incurred in stages from design to manufacturing was multiplied by the capital recovery factor (CRF) to obtain the annuitised cost (AC). The AC was then divided by the annual production output (PO) to obtain the life cycle cost of impeller production ($\mathrm{LCC}_{\mathrm{Impeller,prod.}}$) (Eq. (5)). The annuitised cost was converted to the price of an impeller (PI) using a profit margin (PM) of 35% [44] (Eq. (6)).

$$\mathrm{LCC}_{\mathrm{Impeller,prod.}} = \left(\mathrm{PV}_{\mathrm{Capital}} + \mathrm{PV}_{\mathrm{Labour}} + \mathrm{PV}_{\mathrm{Energy}} + \mathrm{PV}_{\mathrm{O\&M}}\right) \times \mathrm{CRF}/\mathrm{PO} \tag{5}$$

$$PI = \mathrm{LCC}_{\mathrm{Impeller.prod.}} \times (1 + PM) \tag{6}$$

Step 2: This determines the costs associated with the use of impellers in a commercial application. The calculated price of an impeller for pumping operation is considered as capital cost and the cost of electricity used for running this impeller is known as operating cost. $\mathrm{LCC}_{\mathrm{pump\ usage}}$ was therefore calculated by adding the PV of the price of an impeller (PI) to the operational costs during the service life (SL). The sum of PVs was multiplied by the CRF to obtain the AC, then divided by the impellers' service life (SL) [31] as presented in Eq. (7) in order to obtain the life cycle cost of pumping over the impeller SL ($\mathrm{LCC}_{P,SL}$). The study did not consider maintenance costs of pump impellers as they were deemed negligible compared to other costs.

$$\mathrm{LCC}_{P,\mathrm{SL}} = (\mathrm{PV}_{\mathrm{PI}} + \mathrm{PV}_{\mathrm{energy}}) \times \mathrm{CRF}/\mathrm{SL} \tag{7}$$

2.6 Eco-efficiency assessment

The EE analysis compares the economic and environmental performance of 3D-printed impellers using the EE portfolio. The EE portfolio positions were calculated using both LCEI and LCC values of impellers [36]. In order for all LCEIs of impellers to convert to the same unit, they have been first normalised by dividing them by corresponding normalisation factors and then these normalised values were multiplied by corresponding weights. These impacts with the same units can then be compared. Each of these impacts is represented in terms of Australian inhabitants producing the same impact per year [45, 46]. The weighting factors were obtained from the results of the consensus survey, as shown in Table 21 in Appendix 1.

In order to obtain the normalised environmental impacts ($\mathrm{NEI}_{\mathrm{i,n}}$), the LCEI values of the pump impeller type 'n' were divided (Eq. (8)) by the appropriate gross domestic environmental impact ($\mathrm{GDEI}_{\mathrm{i}}$/Inh). For each impact category, 'i', $\mathrm{NEI}_{i,n}$ was multiplied by their respective weights (W_i) (Eq. (9) in order to convert all impacts to the same unit so that all impact values could be combined to create a single value of overall environmental impact (EI_{n}) for an impeller 'n'. This EI_n is the number of Australian inhabitants who produced the same amount of environmental impact per year as the impeller of type 'n' [31].

$$\mathrm{NEI}_{i,n} = \frac{\mathrm{LCEI}_{i,n}}{\mathrm{GDEI}_i/Inh} \tag{8}$$

$$EI_n = \sum_{i=1}^{11} \mathrm{NEI}_{i,n} \times W_i \tag{9}$$

The normalised costs (NC_n) were obtained by dividing the life cycle cost (LCC_n) of a pump impeller 'n' with the relevant GDP/Inh (Eq. (10)). The GDP per capita of Australia in 2020 was taken as AUD 74,117 [47]. NC_n is the number of Australian inhabitants who produced the same amount of GDP as the cost of the impeller of type 'n' [31].

$$\mathrm{NC}_n = \frac{\mathrm{LCC}_n}{\mathrm{GDP/Inh}} \tag{10}$$

The environmental impact portfolio position of each impeller 'n' was obtained by dividing the normalised impact by the average value of EIs of all impellers. In contrast, the cost portfolio position was obtained by dividing the normalised cost of each impeller by the average value of NCs of all impellers (Eqs. (11) and (12)) [31].

$$\mathrm{PP}_{e,n} = \frac{\mathrm{EI}_n}{\sum \mathrm{EI}_n/j} \tag{11}$$

$$\mathrm{PP}_{c,n} = \frac{NC_n}{\sum \mathrm{NC}_n/j} \tag{12}$$

The environment to cost relevance ratio ($R_{E/C}$) was calculated as the ratio of mean EI and mean NC (Eq. (13)), which was used to determine the more influential parameter. Following Jayawardane et al. [31], the portfolio positions were revised by incorporating $R_{E/C}$ (Eqs. (14) and (15)). The revised portfolio positions ($\mathrm{PP'}_{\mathrm{e,\,n}}$, $\mathrm{PP/'}_{\mathrm{c,\,n}}$) were plotted in the EI_{n} vs. NC_{n} graph (Fig. 7).

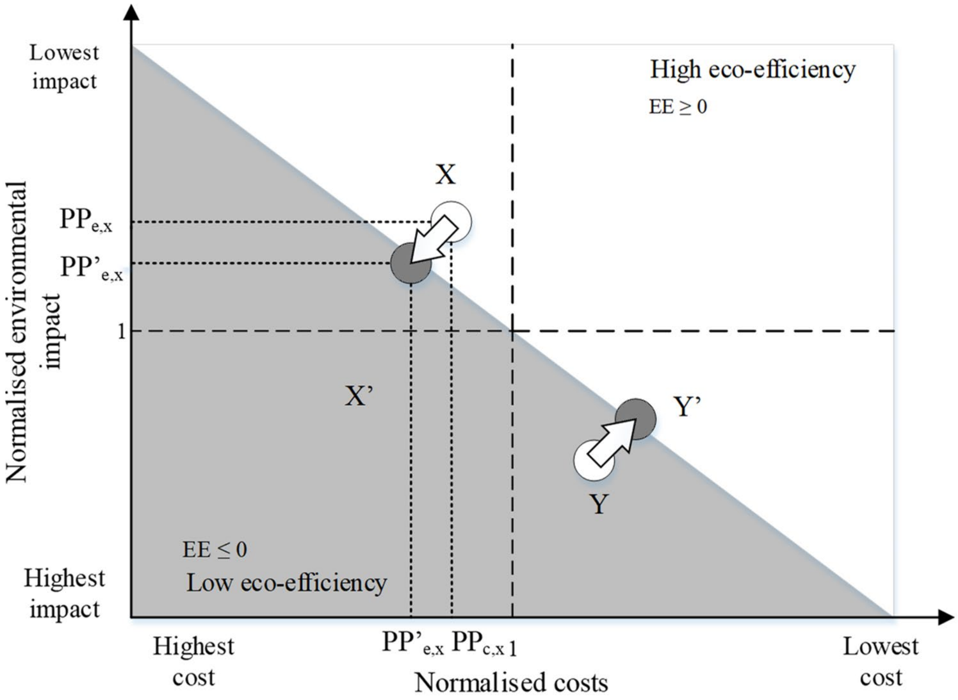


Fig. 7 EE portfolio and positions [31]

$$R_{E/C} = \frac{\sum EI_n/j}{\sum NC_n/j} \tag{13}$$

$$\mathrm{PP'}_{\mathrm{e,n}} = \frac{\left[(\sum \mathrm{PP}_{\mathrm{e,n}})/j + [\mathrm{PP}_{\mathrm{e,n}} - ((\sum \mathrm{PP}_{\mathrm{e,n}})/j)] \cdot \sqrt{(R_{E/C})}\right]}{(\sum \mathrm{PP}_{\mathrm{e,n}})/\mathrm{j}} \tag{14}$$

$$\mathrm{PP'}_{\mathrm{c,n}} = \frac{\left[(\sum \mathrm{PP}_{\mathrm{c,n}})/j + [\mathrm{PP}_{\mathrm{c,n}} - ((\sum \mathrm{PP}_{\mathrm{c,n}})/j)] / \sqrt{(R_{E/C})}\right]}{(\sum \mathrm{PP}_{\mathrm{c,n}})/\mathrm{j}} \tag{15}$$

The eco-efficiency portfolio positions were determined by following the eco-efficiency method by BASF [48]. In this EE portfolio, the most eco-efficient choice has the greatest perpendicular distance above the diagonal line. Due to the integration of the $R_{E/C}$, any changes in the cost or environmental impact of an impeller results in a change of EE portfolio positions of all impellers, as expressed by Eqs. (14) and (15). The impellers which are below the diagonal line were deemed environmentally inefficient, necessitating additional environmental and economic modifications to stay above or at least on the diagonal line.

3 Results and discussion

3.1 Technical feasibility assessment

3.1.1 Density

A mean product density of 7.78 g.cm^{-3} was obtained for the 3D-printed stainless steel impellers. In comparison, a mean product density of 7.94 g.cm^{-3} was obtained for the CNC-machined steel impellers in a density measurement using the specific gravity method at 22.1 °C. The metal 3D-printed sample indicates a relative density of 97.99% in the BMD 3D-printing process [23], resulting in a 316L stainless steel material with similar physical properties to bulk material properties. The presence of low internal voids, porosity, and defects could have led to the higher relative density in the metal AM sample. As a result, this could result in the sacrifice of tensile and fatigue outcomes slightly. Since the mean product density of typical metal injection moulded components (i.e., 7.6 g.cm^{3}) is lower than the mean product density of BMD parts, this reasonably confirms the technical feasibility aspects of the 3D printed impeller in terms of density.

3.1.2 Surface roughness

The surface roughness measurement showed the following results for the mean surface roughness (R_a) of the impeller shroud and the vanes, as presented in Table 3.

Table 3 Surface roughness measurement results

Impeller	Shroud R_a (μm)	Deviation (μm)	Vane R_a (μm)	Deviation (μm)
AM1	2.05	+1.25	3.98	+3.18
AM2	2.03	+1.23	3.36	+2.56
AM3	1.92	+1.12	3.60	+2.80
SM1	0.92	+0.12	0.45	−0.35
SM2	0.93	+0.13	0.47	−0.33
SM3	0.92	+0.12	0.47	−0.33
OEM	0.80		0.80	

The 3D-printed stainless steel impellers showed a slightly higher surface roughness than the CNC-machined stainless steel impellers in the shroud. This indicates an increase in surface roughness caused by the presence of print lines in the *XY*-direction for 3D printing. Furthermore, the surface roughness of the vanes was much higher than the surface roughness of the shroud, which indicates an increase in surface roughness due to the weaker layer stacking in the *Z*-direction for 3D printing. However, the surface roughness of the 3D-printed impellers was measured in the ‘as printed’ state and CNC-machined impellers were measured in an ‘as machined’ state before conducting any finishing CNC-machining operations. This was done to ensure that the surface roughness induced by additive and subtractive manufacturing processes could be directly compared.

Further finishing operations such as post polishing of pump impellers have not been incorporated in the selected pump impeller since reasonable surface roughness has been achieved for the low-cost application of the OEM pump for pumping wastewater. However, pump impellers and integrally bladed rotors in complex applications need further finishing operations such as abrasive flow machining [49, 50] to improve surface properties, which could yield better hydraulic performance. Post polishing could thus be considered in the future study.

3.1.3 Dimensional tolerance

The dimensional tolerances of the 3D-printed pump impeller and the CNC-machined pump impeller are presented in Tables 4 and 5. In 3D-printed impellers, the dimensions of the inner diameter did not meet the fitting tolerance with the pump shaft. CNC-milling machining operation was conducted to increase the inner diameter of the coupling hole of the impeller. Furthermore, the external diameters of the 3D-printed pump impellers were slightly higher than the OEM specification. However, this was allowable due to clearance between the impeller and the pump housing.

Higher dimensional tolerance values were observed in AM impeller due to the part shrinkage during the heat

Table 4 Dimensional measurements of pump impellers

Impeller	Inner diameter (mm)	External diameter (mm)	Vane thickness (mm)	Shroud thickness (mm)	Height (mm)
AM1	7.48	90.16	2.76	1.18	13.13
AM2	7.45	91.25	2.84	1.05	12.78
AM3	7.52	91.34	2.91	1.13	12.83
SM1	8.08	90.15	3.05	1.12	12.91
SM2	8.10	90.05	2.95	1.15	13.05
SM3	8.05	90.21	3.12	1.20	13.12
OEM	8.00	90.00	3.00	1.10	13.00

treatment process of the *Desktop Metal* Studio. Even though parts with a higher solid–cavity ratio have not exhibit high dimensional tolerances in other studies [26], parts with a lower solid–cavity ratio, such as a pump impeller, have shown high dimensional tolerances. The lower dimensional tolerances in shroud thickness and height measurement could be due to the lower shrinkage of parts in *Z*-direction in metal AM [14]. The CNC-machined pump impellers (SM1, SM2, and SM3) showed significantly better dimensional tolerances compared to the 3D-printed counterparts due to precision control of CNC equipment for machining bulk 316L stainless steel material.

3.1.4 Geometric tolerance

The geometric tolerance values were measured by a distance map between the superimposed scanned model and the 3D CAD model (Fig. 8), resulting in an absolute deviation of 0.113 mm and a root mean square deviation of 0.154 mm. The overall geometric measurements of the distance map indicate allowable tolerances as shown in the green region of the superimposed comparison image. Higher deviations were observed along the pump impeller vanes, but they were within the allowable range.

3.1.5 Tensile properties

The results show (Table 6, Fig. 9) slightly higher yield strength and slightly higher ultimate tensile strength values for 316L stainless steel bulk material compared to a stainless steel 3D-printed material. However, the 3D-printed specimens exhibited a more significant percentage elongation at the point of rupture, showing their superior ductile properties. The slightly lower tensile properties of AM specimens could be due to the lower relative density (97.99%) with the presence of internal voids, high porosity, and defects, which could lead to crack propagation. The tensile test results were similar to the results of 316L stainless steel material published by *Desktop Metal* (AM-DM) [23], Sadaf et al. [26], Gong et al. [51], and also similar to the tensile properties of 316L stainless steel specimen produced in metal injection moulding (MIM) [52].

Table 5 Dimensional tolerances

Parameter	AM (mm)	SM (mm)
Inner diameter	±0.50	±0.10
External diameter	±1.50	±0.25
Vane thickness	±0.25	±0.15
Shroud thickness	±0.10	±0.10
Height	±0.25	±0.15

3.1.6 Fatigue properties

The results of the fatigue properties were fit using the Basquin's model (Eq. (1)) for the finite fatigue life region of the material to obtain the Basquin's curve values (Table 7).

Figure 10 shows the logarithmic representation of the fatigue strength for 3D-printed (AM) and CNC-machined (SM) specimens. The results show that 3D-printed specimens possess similar fatigue life compared to that of CN-machined specimens when extrapolated with the Basquin's curve. This is due to the similar ultimate tensile strength values of both specimens contributing to similar fatigue strengths.

The results of the S–N curves of the fatigue test were used for the fatigue life calculation. The maximum pressure load acting on the impeller vanes at the steady-state operating conditions of the pump was set to 10 MPa [31, 53]. The fatigue strength was calculated as the stress value at 10^6 no. of cycles to failure. Table 8 shows the fatigue life calculations of the impellers. Jiang and Ning [25] have conducted a similar study investigating the fatigue strength of BMD 316L stainless steel, which showed a tensile fatigue strength of 100 MPa for 10^6 cycles. The results are also similar to the fatigue strength estimation of 316L stainless steel in SLM by Wang et al. [54].

The specimens exceeded the fatigue limit under cyclic loading. Therefore, it implies that the stainless steel impellers could last an infinite fatigue lifetime under standard steady-state operating conditions. However, this means that failure mechanisms, including foreign object impact damage, thermal damage, erosion, corrosion, and cavitation could determine the impeller service life. Hence, the estimated impeller service life for a submersible pump in standard operating conditions was determined as '1600 h' through the literature review. A pump usage of 4 h per day for 20 days a month (20 months) was estimated for the impellers for the use stage calculations [55, 56].

3.1.7 Surface properties

The morphology of the fracture surfaces of the tensile specimens was observed under the Olympus BX51

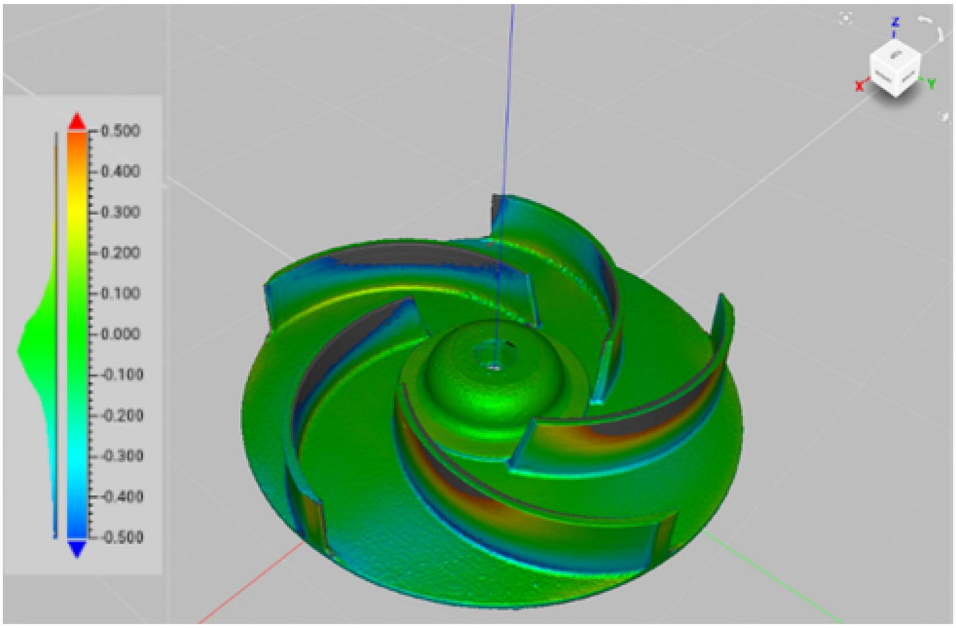


Fig. 8 Geometric tolerance distance map (scale is in mm)

light microscope. The metal 3D printed fracture surface showed a higher percentage of cavities, porosity, and defects (Fig. 11a). The surface topography examination of 3D-printed parts shows the presence of print layers (Fig. 11b–d). In contrast, the surface topography examination of CNC-machined parts (Fig. 11e) does not show any visible defects or porosity in the observed fracture surface of the specimen (Fig. 11f).

3.1.8 Hydraulic properties

The hydraulic performance of the pump impellers was tested using a recirculating pump test rig which resulted in the following data (Table 9) for 3D-printed impellers, CNC-machined impellers, and OEM impeller. The metal 3D-printed impellers and CNC-machined impellers have shown higher flow rates for similar pressure outputs, which indicates that the manufactured impellers are suitable in the application of sewage water pumping with small effluent particles.

Table 6 Tensile test results

Specimen	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Percentage elongation at break (%)
SM1	206.48	509.80	196.43	48.85
SM2	204.60	503.88	185.48	48.83
SM3	203.74	501.48	195.40	44.91
AM1	162.15	463.35	186.01	50.69
AM2	164.35	469.88	198.79	52.85
AM3	169.51	474.59	188.38	49.94
AM-DM	165.00	464.00	152.00	51.00
MIM	175.00	517.00	190.00	50.00

Hydraulic performance curves (Fig. 12) were plotted using the data in Table 9. The results show that metal 3D-printed impellers and CNC-machined impellers outperform the OEM pump impeller in terms of hydraulic performance. This could be due to the weight of 304 stainless steel material used in the OEM pump impeller, which is higher than that of 316L stainless steel material used in metal 3D printing and CNC machining. The effect of higher surface roughness of the metal 3D-printed impeller and CNC machined impeller lowering the impeller performance could have been offset by the difference in weight of the impeller changing the flow curve.

3.1.9 Overall technical performance

The 3D-printed 316L stainless steel pump impeller shows similar properties compared to the benchmark of the CNC machined 316L stainless steel pump impeller. Table 10 presents the summary of the overall technical performance of pump impellers.

The surface roughness of the additive manufactured pump impeller is comparatively higher than that of the CNC machined pump impeller. The surface roughness of the impeller vanes is higher in the AM impeller due to non-uniform surface texture in the *Z*-direction caused by print

Table 7 Basquin's model values for specimens

	AM	SM
A	13,415.29	9323.95
B	−0.3188	−0.2776

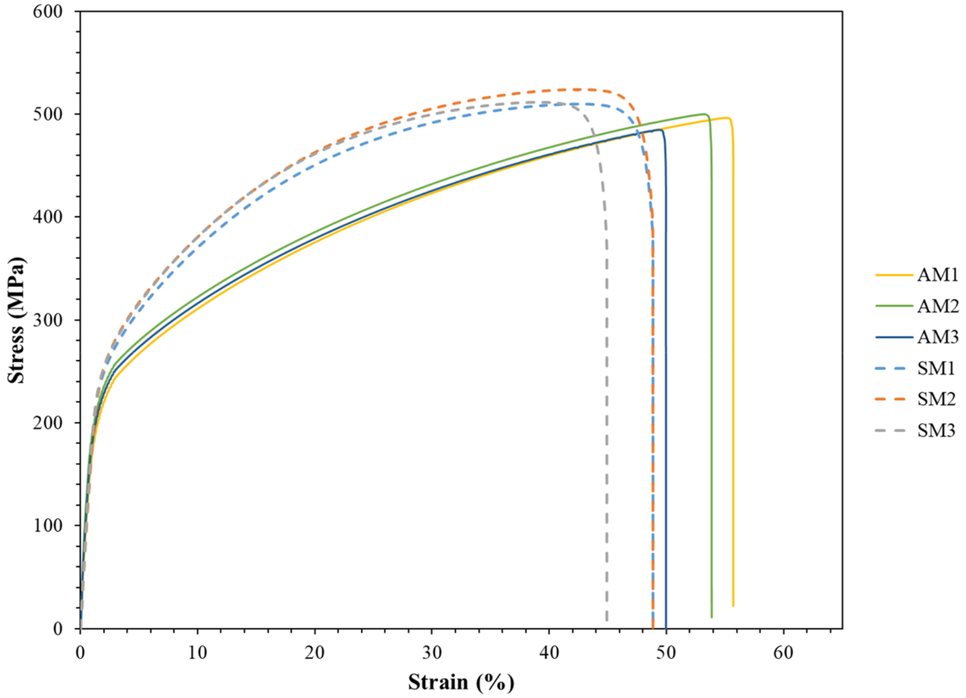


Fig. 9 Stress vs. strain curves for stainless specimens made by AM and SM methods

layers. In the SM impeller, the surface roughness of the shroud is higher due to surface texture from residual cuts from the end milling cutting tool.

The AM specimen has shown a part density of 97.8%, similar to conventional bulk material density. This shows that the sintering process has successfully eliminated the voids of the material, solidifying the 3D-printed material. The tensile strength of the AM material is very close (92.8%) to the tensile strength of the bulk material at an acceptable level, which is similar to the results of Sadaf et al. [26] using metal extrusion AM with 316L stainless steel material. The fatigue strength has slightly reduced (81.6%) due to the AM material having slightly lower tensile strength than the SM material, which was also found in the case of Jiang and Ning [25]. Interestingly, the hydraulic performance of the metal AM impeller was found to be higher than that of the OEM

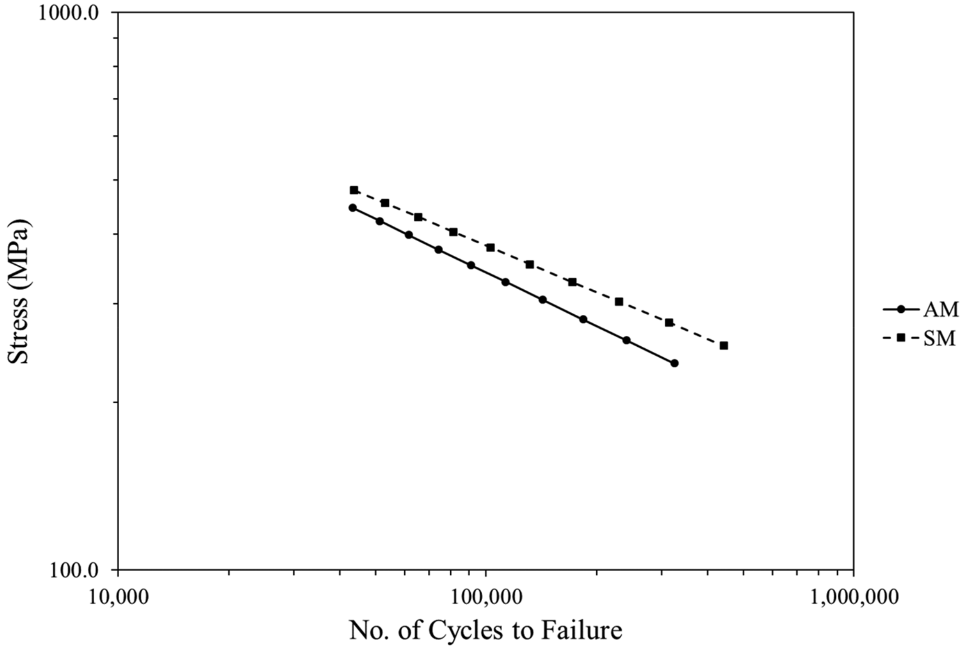


Fig. 10 Basquin's model curve for stress vs. no. of cycles to failure

Table 8 Predicted fatigue life of impellers at a stress of 10 MPa

Configuration (n)	Fatigue strength (MPa) @10^6 cycles	No. of cycles to failure @10 MPa	Fatigue lifetime-estimate (h) @10 MPa
SM	201.37	4.98E+10	2.863E+05
AM	163.98	6.46E+09	3.715E+04
BDM [25]	100	-	-
SLM [54]	200	-	-

impeller. Hence, the overall technical feasibility assessment suggests that a metal 3D printed pump impeller is reasonably technically feasible for the pumping industrial and domestic effluents with particles up to 10 mm.

3.2 Environmental life cycle assessment

Since AM and SM pump impellers were deemed technically feasible through the technical feasibility assessment, they were considered for the environmental life cycle assessment to determine the environmental impact of technically feasible impellers. The environmental impact indicators presented in Table 21 in Appendix 1 has been used in this assessment. The following production plan (Table 11) has been assumed to continue for the useful life of the manufacturing equipment.

The LCI of the pump impellers is presented in Table 12. The 3D printer has a comparatively higher material footprint than the CNC machine due to the combination of equipment (3D printer, debinder, and sintering furnace) needed for the complete metal extrusion process. Furthermore, the manufacturing stage energy consumption of the 3D-printed impeller has also increased due to the energy-intensive final sintering process (84%).

The following LCEI values were obtained for different impellers, as presented in Table 13. The metal 3D-printed impellers (AM) have shown higher LCEI values for environmental indicators such as GWP, europhication, land use, water use, ADP, acidification, particulate matter, and photochemical smog, which is similar to the results of Peng et al. [7]. However, CNC machined impellers (SM) have shown higher LCEI values for human toxicity (148%), freshwater eco-toxicity (304%), marine eco-toxicity (104%), and terrestrial eco-toxicity (39%). These values are consistent with the findings of Ingarao et al. [8]. The subtractive manufacturing process generates large amounts of metallic waste combined with cutting fluids, which could cause eco-toxicity of the land, freshwater bodies, and marine water bodies, and eventually cause human toxicity. After evaluating the environmental impacts, the economic impacts should be determined for further analysis in eco-efficiency assessment.

3.3 Life cycle costs

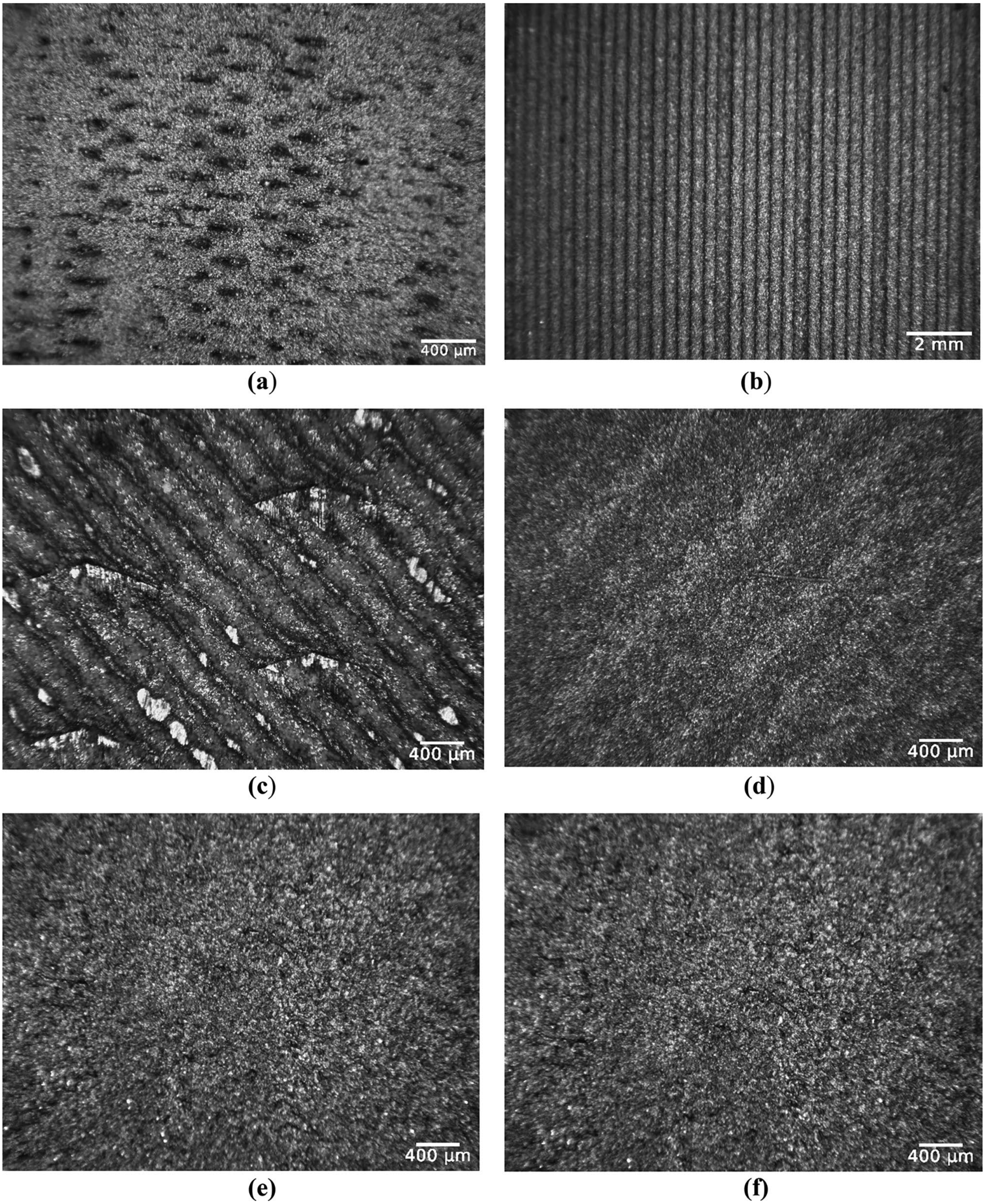
The life cycle costs have been determined for material processing, manufacturing, and usage stages. Table 14 presents the cost information input of the metal 3D printer (printer, debinder, sinter) and the CNC machine (lathe machine, milling machine) for the LCI data. These costs were then incorporated to determine the present values (PVs) of the material processing stage and manufacturing stages of the impellers (see Table 22 in Appendix 2).

The PVs of the material processing and manufacturing stages were used to calculate the PV of production costs according to the production plan. Table 15 presents the calculation of the prices of the impellers (PI) based on the production costs, annuities, and profit margin. A capital recovery factor (CRF) of 0.102 was used to convert the $PV_{\text{total, prod}}$ into annuities. The CRF was determined by the equipment's number of years of operation (10 years) and the discounting factor (7%). The annuities were then divided by the production output to obtain the $LCC_{\text{impeller, prod}}$, which is then converted to the price of the impeller after incorporating a profit margin of 35%.

The price of 3D-printed impellers and conventionally manufactured impellers were incorporated into the life cycle cost calculation as the capital cost. The energy consumption in pump operations was considered as the only operation and maintenance cost of the pump. Service costs and replacement costs of the pump were not considered since similar costs were incurred in both scenarios, and they cancel each other out. These LCC values were used to calculate the present value of the pump usage costs, as shown in Table 16. Firstly, the amount of energy consumed to pump water by each AM impeller and SM impeller was calculated while maintaining a fixed pressure head of 35 kPa. An impeller life of 1600 h or 20 months were estimated for both the AM and SM impellers, as per the fatigue life estimations in the previous technical feasibility assessment. A pump usage scenario of 4 h per day for 20 working days per month was assumed to calculate the pump's energy consumption (see "Sect. 3.1.7").

The results show that the AM impeller has a 2.1% higher cumulative electricity consumption than the SM impeller. This could be due to the lower hydraulic efficiency of the AM impeller (η = 74%) compared to the SM impeller (η = 78%). Furthermore, the capital cost of the AM impeller, which is 90.5% higher than the capital cost of the SM impeller, has resulted in a higher $PV_{\text{total,p}}$ for the AM impeller.

Table 17 presents the total life cycle cost of each impeller during the service life. The results show that the cost of pumping using a metal 3D-printed impeller is significantly more expensive than that for a CNC machined impeller. The equipment cost of metal 3D printing is approximately 4.25



(a) (b) (c) (d) (e) (f)

Fig. 11 Metal AM surface (**a**, **b**, **c**, **d**) and metal SM surface (**e**, **f**)

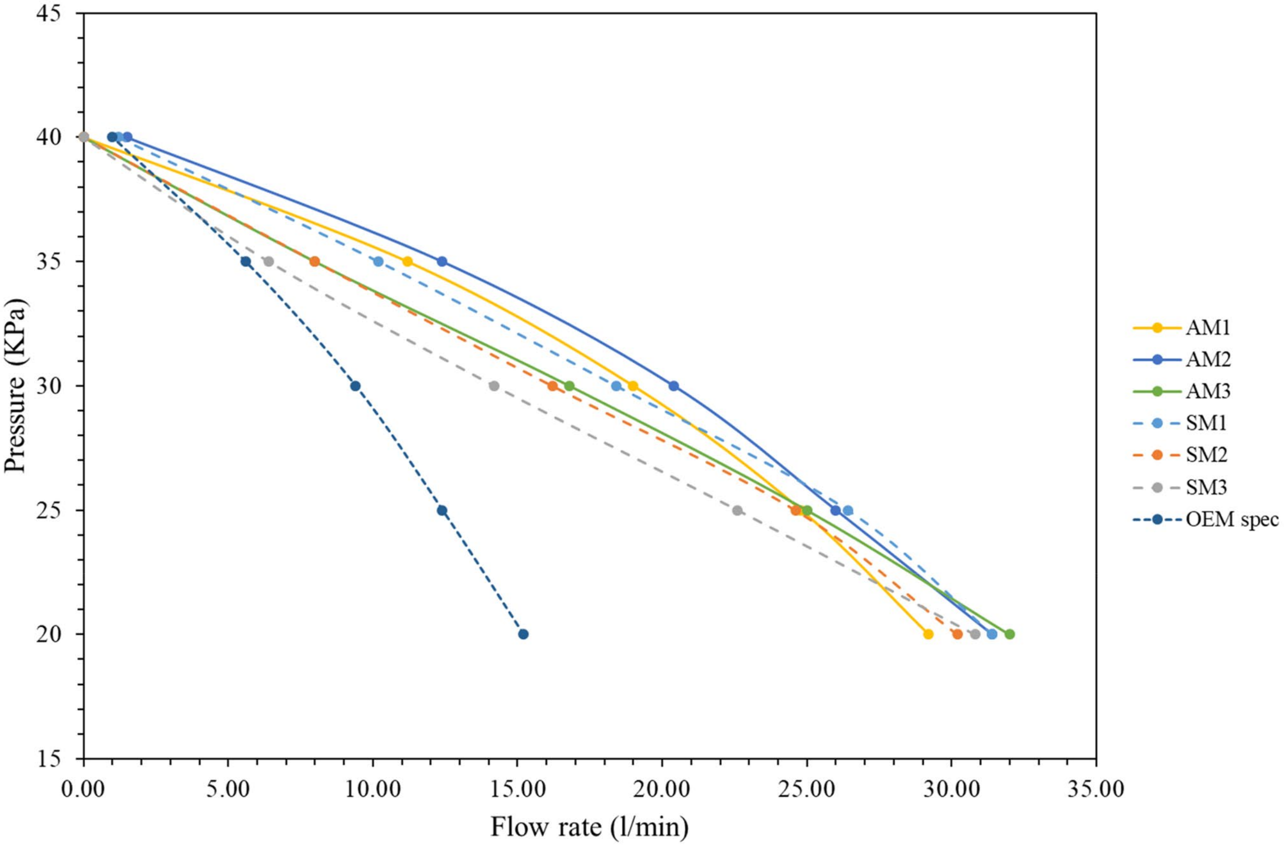


Fig. 12 Hydraulic performance curves

times higher than the equipment cost of CNC machining, which has resulted in very high capital costs. The novelty of the metal 3D-printing technology has resulted in high costs, which is similar to the cost results of Thompson et al. [17]. The equipment costs could reduce in the future with the widespread adoption of metal 3D-printing technology similar to the adoption of fused deposition modelling of thermoplastics [5]. However, due to the additive nature of metal 3D-printing technology, material wastage has been minimised. This is reflected in the production costs of the AM impeller, which is one third lower than the CNC machined impeller. Due to the high solid-to-envelope ratio of the semi-open pump impeller, a large amount of material needs to be removed in CNC machining, resulting in high material costs.

The overall $LCC_{P,\,SL}$ cost of AM impeller is 1.78 times higher than the SM impeller. Life cycle costing warrants further investigation with the integration of environmental

Table 9 Hydraulic performance data

		Pressure Output (kPa)				
	Impellers	20	25	30	35	40
$Q^{'}$ (l/min)	SM1	31.40	26.40	18.40	10.20	1.20
	SM2	30.20	24.60	16.20	8.00	0.00
	SM3	30.80	22.60	14.20	6.40	0.00
	AM1	29.20	24.80	19.00	11.20	0.00
	AM2	31.40	26.00	20.40	12.40	1.50
	AM3	32.00	25.00	16.80	8.00	0.00
	OEM	15.20	12.40	9.40	5.60	1.00

impacts per dollar invested in the manufacturing process. Hence, an eco-efficiency assessment has been conducted to determine the eco-efficiency of metal 3D-printed impellers (AM) and CNC-machined impellers (SM).

3.4 Eco-efficiency Assessment

Since the metal 3D-printed impeller demonstrated about the same level of performance as the CNC-machined impeller, their eco-efficiency assessment could be conducted using ELCA and LCC results. Table 18 presents the normalised environmental impacts of AM and SM impellers after weighting and normalising to allow comparison between the two processes. The results show that NEI for an AM impeller was 55% lower than the SM impeller. When considering individual environmental impact indicators in Table 18, eco-toxicity was found to be the most significant indicator (49% of AM and 76% of SM) contributing to the total environmental impact with the highest contribution from the marine eco-toxicity (36.69% in AM and 67.37% in SM). This could be due to the use of toxic metals in the manufacturing stage, including aluminium, steel, copper, polycarbonates, and other plastics used in the production of manufacturing equipment (Table 12). The 316L stainless steel material used as the feedstock for AM and SM could end up in landfill or aquatic environments as manufacturing stage waste or as end-of-life products.

The next significant impact for metal 3D printing is the cumulative energy demand, which accounts for 15.95% of the AM total environmental impact. The AM energy demand is higher due to higher energy consumption in the manufacturing stage, which accounts for 76.2% of the energy consumption. The LCI values show that the metal sintering process is the most energy-intensive process in metal 3D printing, accounting for 84% of the total energy consumption. The printing process accounts for 5% of the CED, while the debinding process accounts for 10% of the CED. The GWP (10.46%) and photochemical smog (10.65%) are significant contributors to the total environmental impact of the metal 3D-printed products. The manufacturing stage of metal 3D-printing significantly contributes to the GWP (76.3%) and photochemical smog (75.6%).

The subtractive manufactured impeller exhibits a higher environmental impact, significantly contributed by the marine eco-toxicity. In order to obtain the shape of the semi-open impeller, a large amount of feedstock material needs to be removed from the work blank due to the lower solid-to-envelope ratio. This lower material efficiency of the subtractive manufacturing process produces metallic waste combined with coolant fluid, resulting in the release of metallic ions such as chromium or nickel. These metals are constituents of 316L stainless steel (composition: carbon 0.03%, chromium 16–18%, nickel 10–14%, manganese 2%, and molybdenum 2–3%) and could cause significant toxic effects [57]. These significant impact values are identified as hotspots in the ELCA. The normalised environmental impact values not only depend on the LCI inputs used in the product life cycle but also on the weighting factors determined by the consensus survey responses, which indicates GWP as the most significant (11.44%) followed by CED (11.44%). In comparison, land use is the least significant indicator (8.83%) out of the selected environmental impact indicators.

W_i weights, *EI* environmental impact, *TC* total contribution, *MPC* material processing stage contribution, *MfgC* manufacturing stage contribution; *UseC* use stage contribution, *GWP* global warming potential, *ADP* abiotic depletion potential, *CED* cumulative energy demand

Table 19 presents the overall normalised costs and normalised environmental impacts of the AM and SM impellers. These values were calculated according to Eqs. (8)–(10). The LCC values were normalised by dividing with the Australian GDP/Inh value of AUD 70,396.68 as of 2020.

The results show that the metal 3D-printing process could reduce the normalised environmental impact of conventional subtractive manufacturing by 54.6% lower than the conventional process. The substantial reduction of environmental impacts, such as marine eco-toxicity, in metal 3D printing, is reflected in this overall reduction of normalised environmental impact. However, the normalised cost of the metal 3D-printing process has increased the NCn by 43.8% higher than the conventional subtractive manufacturing process. This result infers that the capital costs of metal 3D printing should be reduced, which is expected to become possible by economies of scale after the widespread adoption of the technology. Integration of these values is needed to determine the environmental impact per dollar invested in this technology by conducting an eco-efficiency assessment.

The normalised environmental impacts and normalised costs have been used to determine the initial eco-efficiency portfolio positions. The $R_{E/C}$ value of 0.973 was obtained from Eq. (13), which shows that environmental impacts are almost as influential as the costs. The portfolio positions as presented in Table 20 were calculated from the Eqs. (13)–(15). Moreover, these portfolio positions were plotted on the graph of normalised environmental impact vs normalised cost, as shown in Fig. 13.

The results of the eco-efficiency portfolio show that the metal 3D-printed impeller has a portfolio position above the diagonal, whereas the CNC machined impeller has a portfolio position below the diagonal. This infers that the metal 3D printed pump impeller is eco-efficient whilst the CNC machined pump impeller is not eco-efficient. Compared to the CNC-machined impeller, the metal 3D printed impeller has attained eco-efficiency due to having a significantly lower normalised environmental impact (54.6%) than the former. The lower normalised

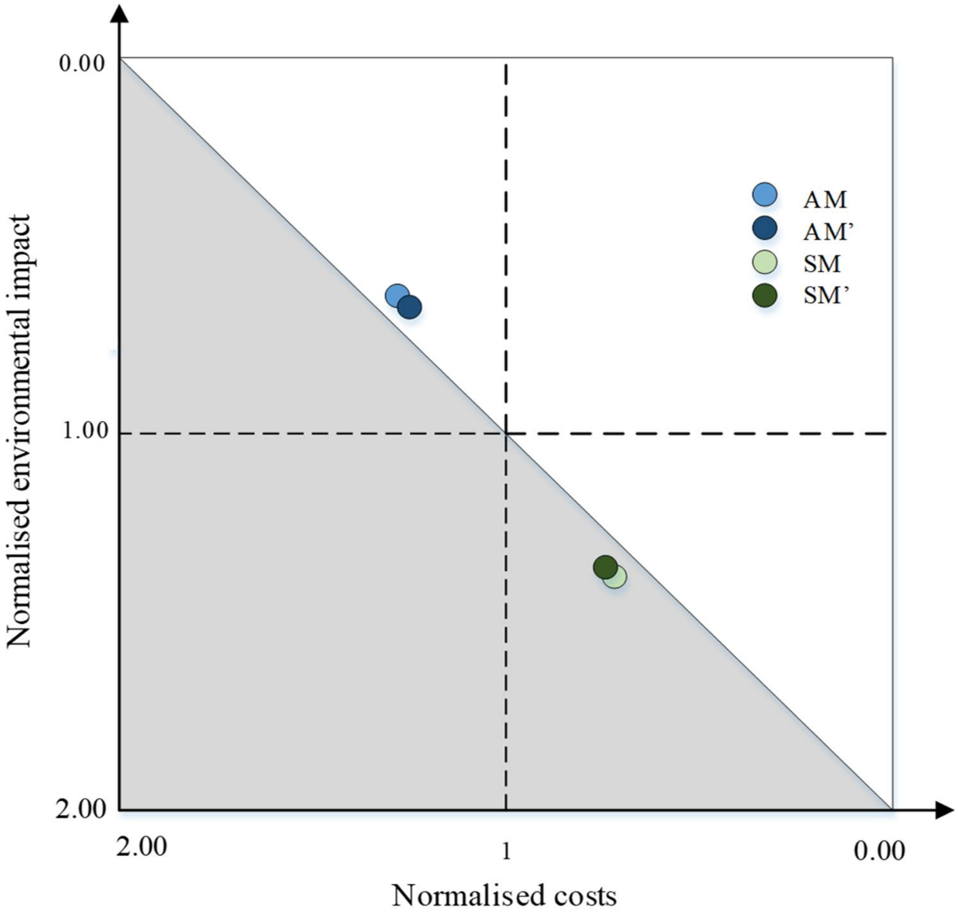


Fig. 13 Eco-efficiency portfolio. (AM, portfolio position of 3D-printed impeller; SM, portfolio position of CNC-machined impeller; AM', revised portfolio position of 3D printed impeller; SM', revised portfolio position of CNC machined impeller)

environmental impact of metal 3D printing is due to a 75.4% reduction of marine eco-toxicity. This shows that metal 3D printing has significant potential to reduce the environmental burden of conventional metal manufacturing. Even though the overall normalised cost of the metal 3D-printed impeller is higher (43.8%) than the CNC-machined impeller, the effect has been offset by the significant reduction of the normalised environmental impact.

The CNC-machined pump impeller has been deemed eco-inefficient due to the significant normalised environmental impact associated with the manufacturing process. This has been significantly contributed by the higher eco-toxicity, which could be due to higher feedstock material wastage in the subtractive process which would end up in landfill or aquatic bodies [16]. The conventional subtractive manufacturing process also uses cutting tools made of carbide or titanium, which possess limited tool life compared to toolless metal 3D printing. The cutting fluids, which are used to reduce the friction and lower cutting temperature, could also pose significant environmental consequences when disposed to a landfill or aquatic bodies, causing significant eco-toxicity, as evidenced by the ELCA results (Table 18).

Even though the metal 3D-printing process is eco-efficient, it still has a significantly higher cumulative energy demand, which is 40% higher than conventional manufacturing. The metal 3D-printing technology should be further developed to reduce

Table 10 Overall technical figures

Parameter	AM	SM
Surface roughness (shroud R_a) (µm)	2.00	0.923
Surface roughness (vane R_a) (µm)	9.65	0.163
Density (g/cm^3)	7.78	7.94
Dimensional tolerance (mm)	± 1.50	± 0.25
Tensile strength (MPa)	469	505
Fatigue strength (MPa) at 10^6 cycles	164	201

Table 11 Production plan of impellers

Parameter	AM	SM
Total manufacturing time (hours) per impeller	25.92	6.23
The estimated lifetime of manufacturing equipment (years)	10	10
Annual production output (PO)	101	319

Table 12 LCI of 3D-printed impellers

Stage	Material/process	AM	SM	3D printer	CNC machine
Design	**Energy (kWh)**				
	CAD modelling	0.45	0.45	-	-
Processing	**Transportation (tkm)**				
	Sea	7.33	10.82	21,762.60	17,737.80
	Land	0.02	0.02	54.34	40.00
Manufacturing	**Primary material (kg)**				
	316L stainless steel feedstock	0.343	1.22	-	-
	Wax	0.019	-	-	-
	Polymer binder	0.003	-	-	-
	Material for machines (kg)				
	Steel	-	-	313.50	636.00
	Cast iron	-	-	-	960.00
	Aluminium	-	-	216.03	400.00
	Other plastic	-	-	169.10	2.00
	Copper	-	-	73.15	2.00
	Energy (kWh)				
	3D printer	2.40	4.45	-	-
	Debinder	4.57			
	Sinter	37.97			
	CNC lathe	-	0.58	-	-
	CNC mill	-	2.87	-	-
	Wire EDM	-	0.77	-	-
	Spot welding	-	0.19	-	-
Use	**Energy (kWh)**				
	Use stage	13.2	13.2	-	-

energy consumption, which is particularly significant (84%) in the metal sintering process. Research should be made to investigate the impact of reducing sintering time, sintering temperature, and changing the sintering profile, together with their influence on the technical performance of the metal 3D-printed parts. The trade-off of technical performance to lower the environmental impact of manufacturing could be applied to functional components that do not require high technical performance [17].

Table 13 LCEI values of impellers

Impact category	Unit	Total LCEI		LCEI per Inh	
		AM	SM	AM	SM
GWP	kg CO$_2$	5.70E+01	6.52E-01	2.21E-06	2.52E-08
Eutrophication	kg PO$_4^{3-}$ eq	2.34E-02	3.51E-04	9.05E-10	1.36E-11
Land use	Ha. a	2.60E-04	2.78E-06	1.01E-11	1.08E-13
Water use	m^3 H$_2$O	1.55E-01	1.12E-02	5.99E-09	4.33E-10
CED	MJ	7.48E+02	2.53E+00	2.90E-05	9.79E-08
Human toxicity	kg 1,4-DB eq	4.62E+00	1.15E+01	1.79E-07	4.44E-07
Freshwater eco-toxicity	kg 1,4-DB eq	1.36E+00	5.50E+00	5.27E-08	2.13E-07
Marine eco-toxicity	kg 1,4-DB eq	5.48E+03	1.12E+04	2.12E-04	4.33E-04
Terrestrial eco-toxicity	kg 1,4-DB eq	7.09E-02	9.88E-02	2.75E-09	3.82E-09
Acidification	kg SO$_2$ eq	1.76E-01	1.83E-03	6.80E-09	7.07E-11
ADP	kg Sb eq	2.41E-04	1.52E-06	9.31E-12	5.89E-14
Particulate matter	kg PM$_{2.5}$ eq	1.84E-02	1.96E-04	7.13E-10	7.58E-12
Photochemical smog	kg NMVOC eq	1.92E-01	2.15E-03	7.42E-09	8.31E-11

Table 14 Capital cost and replacement cost breakdown

	Metal 3D printer (AUD)	CNC machine (AUD)
Equipment costs[a,b]	310,000	59,000
Transport cost	1044	1998
Installation cost	-	1000
Extruder[a]	1500	-
Build plate[a]	3500	-
Cutting tools[b]	-	2500
Coolant[c] (20L)	-	600

[a] Objective 3D, Australia and JdLC, Curtin University

[b] Leadwell industries, Taiwan

[c] Rocol Ultracut clear, TW polymers and fluids

The normalised costs of metal 3D printing should also be lowered, which is 78% higher than the normalised cost of conventional manufacturing. The cost of the 3D-printed impeller is higher due to higher material costs associated with innovative metal composite material that allows metal extrusion. The *Desktop Metal* Studio system consists of a printer, debinder, and sintering furnace with a high material footprint and high equipment cost, which is 4.25 times higher than conventional subtractive manufacturing equipment. The excessive costs should be reduced by improvement strategies such as redesigning equipment for integration, which could eliminate duplication, replacing non-critical metallic materials with technically feasible cheaper materials such as composites, eliminating equipment idle time, and using cheaper materials such as polymer matrix compounds.

The inputs may change when these improvement strategies have been implemented for identified hotspots, requiring an update to the LCI. As a result, additional ELCA and LCC would be required to obtain these impellers' revised eco-efficiency portfolio positions. Revised eco-efficiency portfolio positions could be used to determine the comparative benefits of the improvement strategies.

Table 15 Price of the impeller (PI)

	$PV_{total, prod.}$ (AUD)	Annuitised cost (AUD)	PO	$LCC_{impeller, prod}$ (AUD)	PI (AUD)
AM	554,848	56,324	101	555.53	750
SM	917,357	93,124	319	291.61	394

Table 16 Present values of the pump usage costs

Month	AM impeller		SM impeller	
	Capital cost (AUD)	O&M cost (AUD)	Capital cost (AUD)	O&M cost (AUD)
0	749.96	-	393.70	-
1	-	3.58	-	3.40
2	-	3.57	-	3.38
3	-	3.55	-	3.37
4	-	3.54	-	3.35
5	-	3.52	-	3.34
6	-	3.51	-	3.33
7	-	3.49	-	3.31
8	-	3.48	-	3.30
9	-	3.46	-	3.28
10	-	3.45	-	3.27
11	-	3.43	-	3.26
12	-	3.42	-	3.24
13	-	3.40	-	3.23
14	-	3.39	-	3.22
15	-	3.38	-	3.20
16	-	3.36	-	3.19
17	-	3.35	-	3.18
18	-	3.33	-	3.16
19	-	3.32	-	3.15
20	-	3.30	-	3.14
Total	749.96	68.83	393.70	65.30
$PV_{total,p}$	818.79		459.00	

Table 17 Life cycle cost of pump usage

	$PV_{total, P}$ (AUD)	Annuitised cost (AUD)	$LCC_{P, SL}$ (AUD)
AM	818.79	537.47	322.48
SM	459.00	301.30	180.78

Table 18 Environmental impacts after normalisation

		AM impeller					SM impeller				
Indicator	W_i	EI	TC	MPC	MfgC	UseC	EI	TC	MPC	MfgC	UseC
GWP	11.44%	2.27E-04	10.46%	3.26%	76.3%	20.1%	1.39E-04	2.91%	33.2%	33.5%	32.9%
Photochemical smog	9.06%	2.31E-04	10.65%	4.71%	75.6%	19.5%	1.19E-04	3.64%	47.6%	26.2%	25.9%
Particulate matter	10.42%	4.27E-05	1.99%	14.8%	67%	18%	4.76E-07	1.20%	70.9%	15.6%	13.4%
Eutrophication	9.51%	1.17E-04	5.39%	5.79%	74.7%	19.2%	2.68E-05	2.50%	27.5%	53.4%	18.9%
Human toxicity	10.08%	1.45E-04	6.67%	8.7%	74.3%	16.8%	3.60E-04	7.52%	23.3%	69.8%	6.74%
Freshwater eco-toxicity	10.08%	8.12E-05	3.74%	15.1%	69.8%	15.1%	1.13E-04	2.36%	19.5%	76.7%	3.8%
Marine eco-toxicity	10.08%	7.97E-04	36.69%	21.6%	65.9%	12.3%	3.22E-03	67.37%	31.7%	62.2%	6.04%
Terrestrial eco-toxicity	10.08%	4.56E-05	2.10%	1.7%	77.3%	21.0%	9.30E-05	1.94%	11.3%	73.5%	15.1%
Land use	8.83%	8.85E-07	0.04%	1.22%	77.4%	21.1%	3.60E-04	0.01%	19.3%	41.1%	39.2%
Acidification potential	8.38%	1.20E-04	5.51%	26.2%	58.8%	14.9%	1.13E-04	5.19%	82.6%	10.1%	7.17%
ADP	9.85%	7.90E-08	0.004%	77.5%	22.4%	0.1%	3.22E-03	0.01%	98.1%	1.85%	0.05%
Water use	10.99%	1.83E-05	0.84%	10.6%	77%	12.2%	9.30E-05	0.56%	15.2%	76.4%	8.29%
CED	11.44%	3.47E-04	15.95%	1.79%	76.2%	22.01%	2.48E-04	4.79%	36.8%	32.6%	30.2%
Total		2.17E-03					4.78E-03				

Table 19 Normalised cost and impact of impellers

Configuration	EIn (inhabitants)	NCn (inhabitants)
AM	2.17E-03	4.58E-03
SM	4.78E-03	2.57E-03

Table 20 Portfolio positions

Impeller	PPe	PPc	PP'e	PP’c
AM	0.6247	1.2816	0.6298	1.2778
SM	1.3753	0.7184	1.3702	0.7222

4 Conclusions, recommendations, and future work

This study has compared the techno-eco-efficiency performance of 316L stainless steel pump impellers made by bound metal deposition metal 3D-printing method and CNC-machining method. The material obtained from metal 3D printing shows a relative density of 97.99% to bulk material density, which is similar to the mean product density of metal injection moulded material. The mean surface roughness of the metal 3D-printed products was slightly higher due to the presence of print lines in the *XY*-direction (+ 1.20 mm) and layer stacking in the *Z*-direction (+ 2.84 mm). Surface treatment methods could improve the surface roughness of these specimens. The tensile test showed ductile properties for the metal 3D-printed specimens with a mean yield strength of 165 MPa, mean tensile strength of 469 MPa, and mean elastic modulus of 191 GPa. These properties are similar to the tensile properties of 316L stainless steel bulk material and metal injection moulded material. The fatigue test of metal 3D-printed specimens indicated a fatigue strength of 164 MPa, which could withstand more than 10^6 fatigue cycles under the fatigue loading of 10 MPa and therefore represents essentially infinite fatigue lifetime under ideal loading conditions. The hydraulic performance curves showed comparatively higher performance than the OEM pump impeller curve. These results showed that the metal 3D-printed specimen is technically feasible for the application of sewage pump considered.

The ELCA of the metal 3D printed pump impellers showed higher environmental impacts for marine eco-toxicity, cumulative energy demand, global warming potential, and photochemical smog. The cumulative energy demand of metal 3D printing was higher compared to CNC machining due to the energy-intensive sintering process (84% of the cumulative energy demand). The life cycle costs of a metal 3D -printed impeller is 1.78 times higher than a conventional subtractive manufactured impeller. The metal 3D-printed pump impeller was found to be eco-efficient than the CNC-machined pump impeller due to having a 54.6% lower normalised environmental impact than the latter. The cumulative energy demand in metal 3D printing was identified as the environmental hotspot due to the energy-intensive sintering process of metal 3D printing. High material costs and equipment costs exist due to the intellectual properties associated with the novel technology. The eco-efficiency of metal 3D-printed pump impellers could be improved by technological strategies by analysing the sintering profile to reduce uneven part shrinkage, improving technical performance and cost reduction of machines by part integration, replacing non-critical components with cheaper parts, and eliminating equipment idle time.

The metal 3D-printing technology investigated was limited to the bound metal deposition o f 316L stainless steel materials using a *Desktop Metal* Studio printer. In contrast, CNC machining was limited to 316L stainless steel bulk material machining using *Leadwell* CNC lathe machine, *Leadwell V30* vertical milling machine, and *FANUC Robocut* Wire EDM. Furthermore, the results could change with different materials and improved 3D printing and CNC-machining equipment. A new version of the *Desktop Metal* Studio has eliminated the need for a debinder, which would further reduce the manufacturing time, energy consumption, and eliminate the use of chemicals. The benefits of resource minimisation with topology optimisation of the 3D model in 3D printing were not explored as the 3D model was based on the OEM part. The study also did not consider the failure rate of manufactured parts in mass manufacturing as the research mainly focused on the technical feasibility of manufactured impellers. The EE analysis considers a single value of the environmental impact by normalising, weighting, and aggregating the environmental impacts quantified in the ELCA analysis. However, there could be some uncertainties associated with the use of economic and environmental data, which can be addressed in future research using a Monte Carlo simulation.

Future research could conduct a similar techno-eco-efficiency assessment of 3D-printed products using recycled stainless steel feedstock material. Secondly, the surface properties of the metal 3D-printed impellers could be further improved by polishing impeller blade profiles after metal AM could be investigated. Thirdly, a finite element modelling with numerical simulations can be included in the techno-eco-efficiency analysis to optimise the process parameters. These additional tasks can be conducted in the near future to support the adoption of metal 3D-printing technology as a sustainable option in automotive, aerospace, oil and gas, medical, and other industrial applications. Future research should also consider the social implications (e.g., job losses) of the replacement of the conventional subtractive manufacturing supply chain with 3D printing process.

Appendix 1

Table 21 Factors for normalisation and weighing of the environmental impacts [31]

Environment impacts (EIs)	$GDEI_i$	Unit (per inhabitant/y)	Weight (W_i)
Global warming potential (GWP)	28,690	t CO_2 eq	11.44%
Photochemical smog	75	kg NMVOC	9.06%
Particulate matter	45	kg $PM_{2.5}$ eq	10.42%
Eutrophication	19	kg PO_4^{3-} eq	9.51%
Human	3216	kg 1,4-DB eq	10.08%
Terrestrial	88	kg 1,4-DB eq	10.08%
Freshwater	172	kg 1,4-DB eq	10.08%
Marine	12,117,106	kg 1,4-DB eq	10.08%
Land use	26	Ha a	8.83%
Acidification potential	123	kg SO_2 eq	8.38%
Abiotic depletion potential (ADP)	300	kg Sb eq	9.85%
Water use	930	m^3 H_2O	10.99%
Cumulative energy demand (CED)	246900	MJ	11.44%

CO_2 carbon dioxide, *NMVOC* non-methane volatile organic compound, *$PM_{2.5}$* particulate matter, *PO_4^{3-}* phosphate, *DB* dichlorobenzene, *Ha a.*, hectare per year, *SO_2* sulphur dioxide, *Sb* antimony, *H_2O* water, *eq.* equivalent, *MJ* megajoule

Appendix 2

Table 22 PV of the production costs of 3D-printed impeller benchmarked with the production costs of the CNC-machined impeller

	Capital cost		Replacement cost				Manufacturing cost	
Year	3D printer	CNC machine	Extruder	Build plate	Coolant	Cutting tools	AM	SM
0	311044	61998						
1	-	-	2804	0	560.7	2336.4	25,070	102,621.1
2	-	-	4005	0	534.0	2225.1	23,875	97,729.8
3	-	-	3814	3023	508.6	2119.0	22,737	93,071.6
4	-	-	3632	0	484.3	2018.0	21,654	88,635.5
5	-	-	3459	0	461.2	1921.8	20,621	84,410.8
6	-	-	3294	2611	439.3	1830.2	19,639	80,387.5
7	-	-	3137	0	418.3	1743.0	18,703	76,556.0
8	-	-	2988	0	398.4	1659.9	17,811	72,907.0
9	-	-	2845	2255	379.4	1580.8	16,962	69,432.0
10	-	-	2710	0	361.3	1505.5	16,154	66,122.6
Total	14949	64224	32,690	7889	4545.6	18,939.9	203,226	831,873.9

All costs are in AUD

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Declarations

Ethics approval The ethics approval for this research work was obtained from Curtin University under approval number HRE2020-0203.

Competing interests The authors declare no competing interests.

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APPENDIX D – ARTICLE 4

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Authorship agreement

I, Heshan Thenuka Wijerathne Jayawardane, contributed 80% to the paper entitled 'Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment'.

Mr. H.T.W. Jayawardane

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Author	Signature
Ian J. Davies	
J. R. Gamage	
Michele John	
Wahidul K. Biswas	

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ORIGINAL ARTICLE

Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment

Heshan Jayawardane[1] · **Ian J. Davies**[2] · **J. R. Gamage**[3] · **Michele John**[1] · **Wahidul K. Biswas**[1]

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Abstract

Plastic materials have been widely used to replace metals in functional parts due to their lower cost and comparable technical properties. However, the increasing use of virgin plastic material in consumer and industrial applications has placed a significant burden on waste management due to the volume of waste created and the potential negative effects of its end-of-life processing. There is a need to adopt circular economy strategies such as plastic recycling within industrial applications in order to reduce this significant waste management pressure. The present study used recycled polylactic acid (PLA) material as a feedstock for the 3D printing of a centrifugal semi-open pump impeller. The technical performance of 3D printed recycled PLA material and virgin PLA material was compared in this study. The environmental impacts for technically feasible impellers were assessed through the environmental life cycle assessment, while costs were evaluated by life cycle costing. The results were incorporated into a techno-eco-efficiency framework to compare the technical properties, environmental impacts, and costs. The social impacts of additive manufacturing and recycled feedstock material were also explored. The technical assessment results indicated that tensile strength, fatigue strength, density, and hardness decreased with recycled material content compared to virgin material. Microscopy of the fracture surfaces revealed the presence of slightly higher porosity and defects in recycled specimens, which could result in slightly lower technical properties. However, the recycled material was accepted for further ecological analysis as it offered higher pumping performance when compared to the original component and could reduce the burden on virgin material-based production and waste material disposal. Importantly, the results showed that 3D printed recycled PLA impellers are more eco-efficient when compared to 3D printed virgin PLA impellers.

Keywords Recycled plastics · Additive manufacturing · Mechanical characterisation · Eco-efficiency

Abbreviations

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
EEA	Eco-efficiency assessment
GWP	Global warming potential
IMPLA	Injection moulded polylactic acid
NC	Normalised cost
PA	Polyamide
PLA	Polylactic acid
PS	Polystyrene
SLCA	Social life cycle assessment
VPLA	Virgin polylactic acid
ADP	Abiotic depletion potential
CE	Circular economy
ELCA	Environmental life cycle assessment
HIPS	High impact polystyrene
LCC	Life cycle costing
NEI	Normalised environmental impact
PC	Polycarbonate

✉ Heshan Jayawardane
h.wijerath@postgrad.curtin.edu.au

Ian J. Davies
i.davies@curtin.edu.au

J. R. Gamage
gamagejr@uom.lk

Michele John
m.rosano@curtin.edu.au

Wahidul K. Biswas
w.biswas@curtin.edu.au

[1] Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

[2] School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia

[3] Department of Mechanical Engineering, University of Moratuwa, Moratuwa, Sri Lanka

PP	Portfolio position
RPLA	Recycled polylactic acid
UNEP	United Nations Environment Program

1 Introduction

Plastic polymer materials are widely used in industrial and commercial applications due to their technical properties such as durability, corrosion resistance, high strength, light weight, and low maintenance when compared to metallic components [1, 2]. The production of plastic has reached a level of 381 million tonnes per year and 7.8 billion in total by 2015 [3]. However, the use of virgin plastic materials and the disposal of plastics in landfill or water bodies have caused significant environmental impacts such as eco-toxicity and greenhouse gas emissions (1.7 Gt CO_2-eq by 2015) due to their non-biodegradability [4]. The disposal of non-biodegradable plastic waste has increased to 80% of production at an alarming rate in recent years, while only 20% has been recycled [5]. The linear economy that starts from extraction and ends at disposal has depleted natural resources and posed negative environmental impacts such as greenhouse gas emissions, global warming, particulate matter emissions, and eco-toxicity [6]. If the current linear economic trajectory continues, the amount of plastic in oceans is expected to be more than the total biomass of fish by 2050 [4].

Recycling waste plastic into new or usable products can prevent both the material extraction and disposal stages in product life cycles, which could lead to a better circular economy (CE) [7, 8]. The five 'R' strategies, namely, recycling, remanufacturing, repairing, reusing, and refurbishing, can be considered to convert end-of-life products into new or usable products [9]. Figure 1 shows the life cycle stages of a conventional manufacturing scenario with CE strategies incorporated at different life cycle stages. These strategies reduce resource extraction and waste material disposal, thereby significantly avoiding the environmental impacts associated with manufacturing. These allow the plastic products to be recovered after a single life cycle and generate multiple life cycles for materials while maximising their utility and value [3].

Additive manufacturing (AM) or 3D printing has been found to offer higher material efficiency compared to subtractive manufacturing [10]. The use of additive manufacturing has increased by 32% during the last 5 years in the production of machine components [11–13]. Despite these benefits, AM also produces waste material in the form of support structures, failed prints, leftover raw materials, and disposable prototypes [14–16]. It is important to determine the contribution of AM to CE initiatives, such as the potential to use recycled feedstock. The metallic powder material that remains unused in the 3D printer can be recycled up to 95%, while waste metals from several applications can also be easily recycled to AM feedstock [17]. Similarly, the sustainability of recycling plastic waste and the feasibility of using recycled plastic material in AM should be investigated.

It has been found that the carbon footprint of recycled plastic is 3000 times lower when compared to virgin plastic materials [2]. However, the rate of recycling in the global plastic packaging industry still remains at 14% [3]. AM is a feasible manufacturing option to use recycled plastic material as filament feedstock [14]. Common plastic materials used in AM are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyamide (PA/Nylon), and polycarbonate (PC). However, ABS, PA, and PC are petroleum-based and non-biodegradable.

PLA is a biopolymer made from plant materials such as corn starch, which is extensively used as a 3D printing filament feedstock material [18]. The virgin PLA material is available in pellet form, which can be used for filament extrusion and plastic injection moulding [19]. However, virgin PLA production increases the use of corn starch and sugar cane, which could affect the food security of some developing countries [20]. Since a large amount of PLA does not degrade under ordinary conditions, even with microbial action, the end-of-life disposal of commercial PLA parts has become a significant issue [21]. Furthermore, the disposal of waste PLA material also discards valuable raw materials, which could otherwise have been used as an alternative feedstock. Therefore, prolonging the life of PLA through

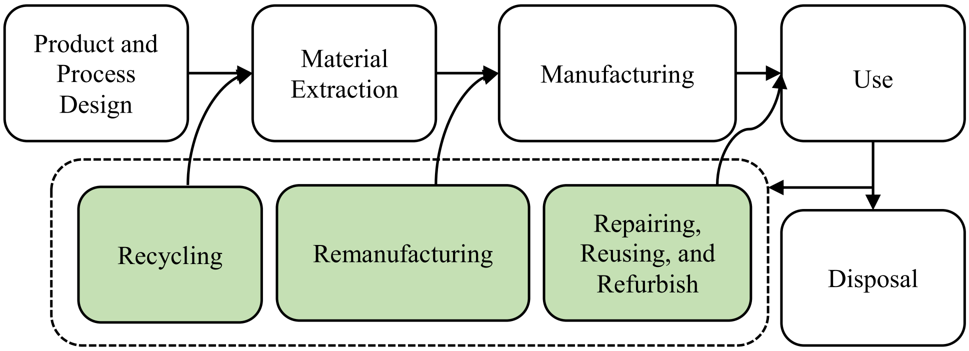


Fig. 1 Manufacturing life cycle stages, adapted from [9]

circular economy strategies, i.e. reuse, recycling, and recovery, is essential to reduce the pressure on virgin materials and minimise waste generation [11]. The waste PLA material could potentially be recycled into 3D printed filament, which could then be used to manufacture parts and reduce environmental impacts [14].

The feasibility assessment of waste plastic as a feedstock material for manufacturing in industrial applications has become a primary target of CE initiatives [22]. The technical properties of recycled plastic are significantly affected by the degree of degradation from multiple melt processing, contamination from other materials during waste collection, and external factors such as ultraviolet radiation [23]. Several studies have been conducted to improve the technical properties of recycled plastics. Mixing recycled plastic with virgin plastic material has become one of the most common approaches to achieving technical properties (97.5% tensile strength and 89.25% flexural strength) closer to virgin material [14]. In addition, recycled plastic materials have also been mixed with fillers [24], stabilisers, compatibilisers, and reinforcement fibres to improve their technical properties [25, 26].

The technical feasibility of recycled PLA material needs to be examined through mechanical characterisation tests such as density, viscosity, surface roughness, dimensional tolerance, tensile testing, fatigue testing, and functional application testing [14, 27]. The durability and service life of the functional parts made from recycled PLA material could also have a significant impact on the selection of recycled feedstock over virgin materials. However, technical data on recycled PLA material was very limited in previous studies. Table 1 presents several studies that have investigated the technical feasibility of recycled plastics, including PLA material. However, these technical assessments did not consider fatigue properties and the feasibility of functional applications of recycled PLA materials. Furthermore, the studies did not integrate the technical feasibility of recycled PLA material with the economic and environmental impact reduction of recycling plastic waste.

Environmental and economic impact assessments are important considerations in terms of circular economy as they quantify different approaches for end-of-life processing of plastic waste for comparison. Several studies have assessed the environmental impact of plastic waste recycling for AM through environmental life cycle assessment (ELCA) methods [14, 29, 30]. For example, Zhao et al. [14] studied the environmental impact of PLA in a closed-loop of 3D printing and recycling. The results show that environmental impacts associated with plastic recycling are significantly lower than other end-of-life processing methods such as incineration and landfill. Choudhary et al. [30] investigated the environmental and economic impacts of polyethylene terephthalate (PET) plastic waste recycling for 3D printing filament production through an ELCA and life cycle costing (LCC). The results show that recycled PET plastic reduces the environmental impacts and associated costs compared to virgin PET plastic. The study also reveals that the integration of renewable energy, such as solar photovoltaic systems, further improves the environmental performance of material recycling.

Implementing strategies to lower environmental impacts in manufacturing has the potential to increase the cost of production [31]. Hence, the environmental impact reduction per dollar invested should also be explored. Eco-efficiency assessment is a widely used integrative assessment framework that determines the environmental impact per dollar invested in the product. Eco-efficiency of plastic waste disposal of PET, polystyrene (PS), and PLA was studied in [32], which showed that PLA material has the highest eco-efficiency. An integrative framework of techno-eco-efficiency was proposed by Jayawardane et al. [26] for the sustainability assessment of additive manufacturing over subtractive manufacturing. The results show that additive manufactured composite material possesses higher eco-efficiency when compared to the subtractive manufactured component. Furthermore, this framework could be applied to assess the techno-eco-efficiency of recycled material feedstock in additive manufacturing.

Table 1 Previous studies on the technical feasibility of recycling PLA material

Material	Tests and results	Reference
PLA	The recycled PLA material was tested for mechanical properties, melt flow rate, and thermal properties through 10 cycles of re-extrusion. Recycled PLA showed acceptable properties as an additive in a material blend	[28]
PLA	The density and tensile properties of recycled PLA were slightly lower than virgin PLA	[6]
PLA	The recycled PLA was tested for tensile, shear, and hardness and exhibited lower properties than virgin PLA	[11]
PLA	The viscosity of recycled PLA deteriorated significantly, while mechanical properties reduced slightly over three cycles	[14]
PLA/cellulose	Recycled PLA blend of 30% wt. and blends of micro-cellulose were tested for technical properties. The recycled PLA blend showed better properties than 100% recycled PLA	[18]
PLA/lignin	The use of lignin fibres improved the tensile properties of PLA material by 7%	[24]
PLA/carbon fibre	Carbon fibre reinforcements improved the tensile, flexural, and impact properties of 73% recycled PLA	[25]

The increased use of additive manufacturing processes shifting from conventional processes could result in numerous social impacts, whereas waste recycling and the use of recycled feedstock materials could also impact society in many ways. Therefore, the social impacts of AM, waste recycling, and the use of recycled feedstock for AM should be systematically evaluated after assessing the technical, economic, and environmental impacts of AM. Even though the social impacts of manufacturing are significant, studies on the social impact assessment on manufacturing are very limited due to the difficulty in measuring relevant indicators. Several studies have evaluated the social impacts of manufacturing on the development of skills, changes to the intensity of work [33], job losses [34], and health and occupational hazards [35, 36]. The social impacts of material recycling and the use of recycled material feedstock have been analysed under the conservation of natural resources and reduction of landfill [37]. However, literature on the social impacts of recycled materials for AM feedstock is difficult to find. Table 2 presents a summary of the results from studies on the social impact assessment of AM and plastic recycling.

The aim of this study is to investigate the techno-eco-efficiency performance of recycled PLA material in comparison with virgin PLA material. The technical, economic, environmental, and social performance of recycled PLA material needs to be determined as a decision support tool for diverting plastic waste as a functional material to maximise utility and value in industrial applications.

2 Materials and methods

Post-manufacturing waste generated during virgin PLA filament manufacturing was used as the feedstock material for the recycled PLA 3D printer filament. The waste material was first separated from other contaminants and then shredded into particles of original pellet size (3 mm). Then the same filament extrusion method as the virgin filament production was used for the recycled material production. Figure 2 shows a process flow diagram of the conversion of

Table 2 Social impact assessments of AM and plastic recycling

Social impacts assessed	Method	Results	References
Level of employment	Social LCA (UNEP)	Skilled employment has increased with AM, while unskilled employment has decreased	[34]
Development of skills	SLCA, qualitative survey	AM aids the development of new skills such as product design optimisation, rapid prototyping, and rapid tooling	[33]
Intensity of work	SLCA, qualitative survey	AM decreases the intensity of work due to lower rework time, defects, and monitoring time	[33]
Occupational hazards	Material safety data	The chemicals and solvents used in AM can cause emissions and toxicity	[35]
	SLCA, quantitative survey	A reduction of occupational incidents (fatal and non-fatal) in AM	[33]
	Polymer weight correlation	The correlation to polymer weight was used to find the human toxicity potential (HTP) of fused deposition modelling AM	[36]
Conservation of natural resources	Energy and material consumption	Material consumption of AM is lower than SM, which contributed to the conservation of virgin material, while higher energy consumption was reported for AM compared to SM	[35]
Reduction of landfill	Diversion of landfill	Plastic waste could be diverted from landfill to construction aggregate to avoid landfill sites	[37]

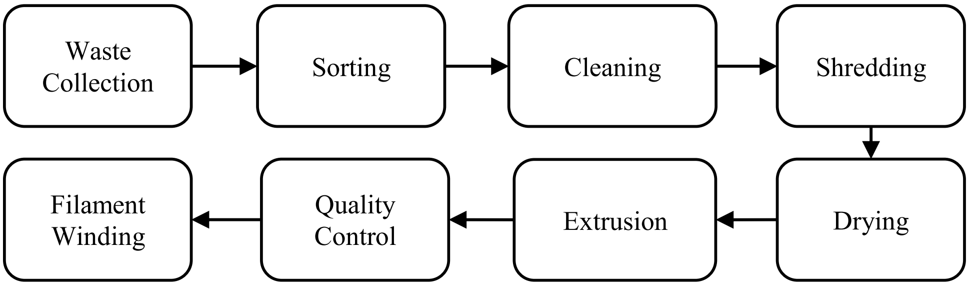


Fig. 2 Recycled filament manufacturing process

waste plastic material into recycled filament material for 3D printing applications.

A semi-open impeller in a centrifugal water pump was used as the functional part in this analysis based on the same criteria (complexity, solid-to-envelope ratio, application, functionality, and availability of performance test) used by Jayawardane et al. [38], with the chosen pump impeller design being taken from a *Grundfos Unilift KP 250* pump.

The techno-eco-efficiency framework (Fig. 3) by Jayawardane et al. [38] has been followed to compare the technical, economic, and environmental performance of pump impellers, which were made of virgin and recycled PLA materials. The technical feasibility of the materials included mechanical, built material, geometrical, morphological, and pump performance tests. The life cycle inventory (LCI) was developed only for technically feasible impellers. The environmental impacts have been quantified by the ISO 14040/44 ELCA method. The life cycle impact assessment (LCIA) was conducted using SimaPro LCA software for indicators selected through an expert survey. The economic value was calculated using the life cycle costing (LCC) method. The environmental impacts were normalised by dividing them by the gross domestic environmental impact per inhabitant (GDEI/Inh.), and then normalised values were multiplied by the relative weights assigned by experts. The costs were normalised by dividing them by the gross domestic product per inhabitant (GDP/Inh.). These normalised environmental impacts and normalised costs were incorporated into the eco-efficiency framework for determining the eco-efficiency portfolio. The eco-efficiency portfolio positions determined the eco-efficiency performance of 3D printed impellers made by recycled feedstock and virgin feedstock. The ELCA could help determine improvement strategies that could be used to improve the 3D printed impellers further.

2.1 Manufacturing

The virgin PLA (VPLA) and 100% recycled PLA (RPLA) 3D printer filament materials were sourced from *Aurarum Pty*, Melbourne, Australia. The injection moulded virgin PLA (IMPLA) material was sourced from *Jeewa Plastics*, Colombo, Sri Lanka. The 3D printed impellers and specimens for technical feasibility tests were manufactured using a *MakerBot Replicator Z18* 3D printer. The specimens for technical feasibility tests of the IMPLA material were made from a 5 mm plate using a computer numeric control (CNC) milling machine. Figure 4 a and b show the RPLA impeller, Fig. 4c and d show the VPLA impeller, and Fig. 4e shows the 3D printer.

The following specifications were set for 3D printing parameters for each configuration (Table 3).

Ideally, the 3D printer process parameters (Table 3) should be the same for both the VPLA and RPLA filaments. However, the disparity in melting temperature and viscosity between the VPLA and RPLA filaments required the use of slightly different process conditions in order to achieve 3D printed components of nominally similar quality. Therefore, the 3D printer process parameters were adjusted for the RPLA material in order to minimise the effects of process parameters on the technical feasibility of RPLA parts compared to VPLA parts. Namely, the nozzle temperature of the 3D printer for RPLA material was increased to 210 °C, the melt flow

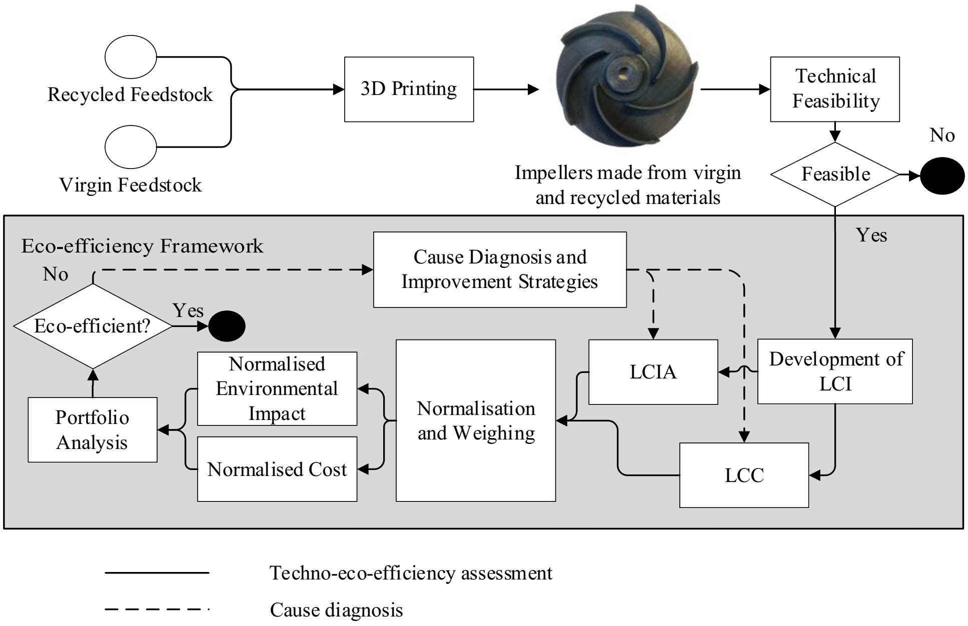


Fig. 3 Techno-eco-efficiency framework [26]

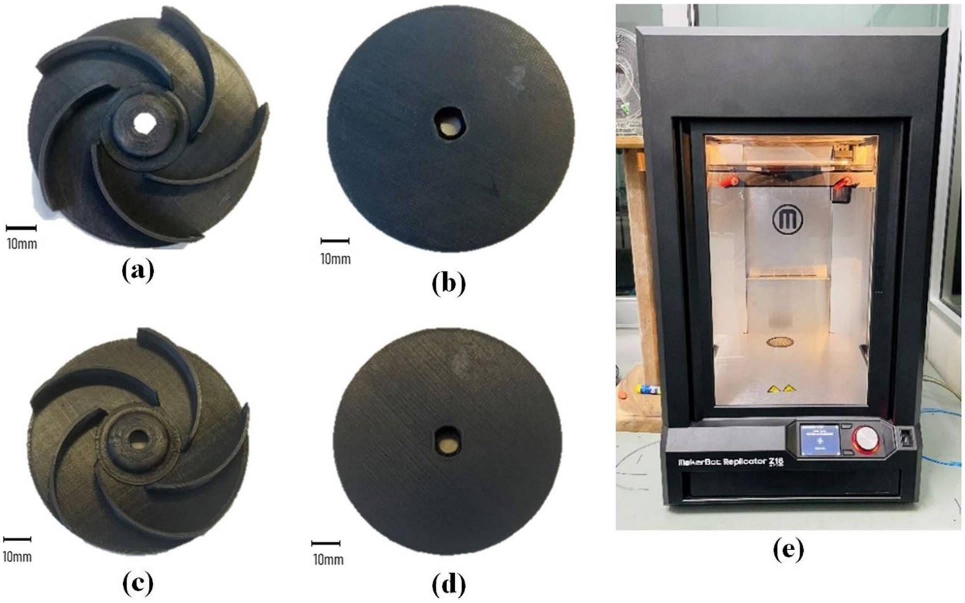


Fig. 4 RPLA impeller, front (**a**); RPLA impeller, rear (**b**); VPLA impeller, front (**c**); VPLA impeller, rear (**d**); and *MakerBot Replicator Z18* 3D Printer (**e**)

Table 3 Specifications for each PLA configuration

Material	VPLA filament	RPLA filament
Nozzle temperature	200 °C	210 °C
Bed temperature	60 °C	60 °C
Melt flow index	100%	110%
Nozzle size	0.4 mm	0.4 mm
Layer height	0.12 mm	0.12 mm
Print speed	60 mm/s	50 mm/s
Raster orientation	0°	0°
Roof and floor layers	4	4
Infill pattern	Cubic	Cubic
Infill density	100%	100%
Retraction (distance @ speed)	5 mm @ 40 mm/s	6 mm @ 50 mm/s

Melt flow index is a measure of ease of polymer flow. Retraction is the return movement of the 3D printer filament to avoid stringing

index was increased to 110%, and the print speed was reduced to 50 mm/s, in order to obtain uniform print extrusion without clogging [14, 39].

2.2 Technical feasibility assessment

The technical feasibility assessment was conducted in order to ensure the feasibility of the RPLA material for the functional application. Technical properties of the printed impeller and specimens were tested to study the mechanical, build material, geometrical, hydraulic performance, and morphological properties, as presented in Table 4.

Table 4 Technical feasibility properties and associated tests

Property	Test
Mechanical property	Tensile behaviour
	Fatigue testing behaviour
Build material property	Surface roughness
	Hardness
	Density
Geometric property	Dimensional tolerance
Hydraulic performance	Pump testing
Morphology	Microscopy of the fracture surface

2.2.1 Density

The density of a specimen is an important characteristic to determine the porosity of the specimen. Since 3D printed specimens have an inherently anisotropic nature due to the layered deposition of material, it is essential to measure the density through a standard method. The density of the 3D printed specimens was calculated by measuring specific gravity following the ASTM D792 standard, method A [40]. The specimens were first weighed in air and then weighed when immersed in distilled water at 23 °C. The density of RPLA and VPLA specimens was compared with the density of the injection moulded PLA (IMPLA) material.

2.2.2 Tensile testing

The tensile properties characterise the material's mechanical strength. Since the pump impeller considered in this study undergoes tensile loading, tensile testing has been considered. The tensile parameters of the PLA specimens, such as ultimate tensile strength (UTS), yield strength, strain at break, elastic modulus, and energy absorption, were tested using a *Testometric* Universal Testing Machine. The ASTM D638 type 1 standard specimens, as shown in Fig. 5, were printed from the same 3D printer. Four specimens of each configuration were tested at a 5 mm/min crosshead speed.

2.2.3 Fatigue testing

The fatigue failure by tensile loading has been considered in this study for the application of a pump impeller. Other failure modes including flexural loading, impact damage, and creep have not been considered in the analysis. According to ASTM D790, the fatigue tests were carried out using a specimen type identical to the tensile testing specimen. The fatigue properties of the PLA specimens were determined using the dynamic loading conditions of the *Testometric* Universal Testing Machine. The fatigue test was conducted by axially loading the test specimens with a stress ratio ($R = \sigma_{min}/\sigma_{max}$) of 0.1. A loading rate of 5 Hz was used in the experiment. Nine un-notched specimens were tested under load-controlled cyclic loading with three specimens for each stress level at 80% of ultimate tensile stress (UTS), 70% of UTS, and 60% of UTS. The number of cycles to failure and the stress levels were plotted as S–N curves using Basquin's model approximation. Equation 1 presents Basquin's model equation where S is the applied stress on the specimen and N is the number of cycles to failure, whilst A and B are material constants. The estimated fatigue life was determined by the number of cycles and pump speed (Eq. 2):

$$S = A \times N^{B} \tag{1}$$

$$\mathit{Estimatedfatiguelife}(h) = N/\mathit{Pumpspeed}(\mathit{cycles}/h) \tag{2}$$

2.2.4 Dimensional tolerance

The dimensional measurements of the 3D printed impellers were taken using a *Mitutoyo* digital vernier calliper (standard error of 0.01 mm). Measurements were obtained from the inner diameter (1), outer diameter (2), shroud thickness (3), and vane thickness (4) of the pump impeller (Fig. 6).

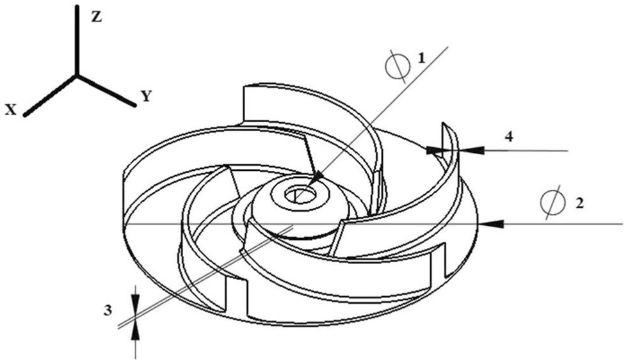


Fig. 6 Reference points for dimensional measurements

Five readings of each feature were measured, with mean values and standard deviations of the measurements being calculated.

2.2.5 Hardness

Following ISO 868 [41], the hardness of each PLA configuration was taken at 20 points of the tensile specimen beginning from the middle section using a handheld *CV DSDS001* Shore Durometer on the D scale. The average and standard deviation of the parameters were calculated.

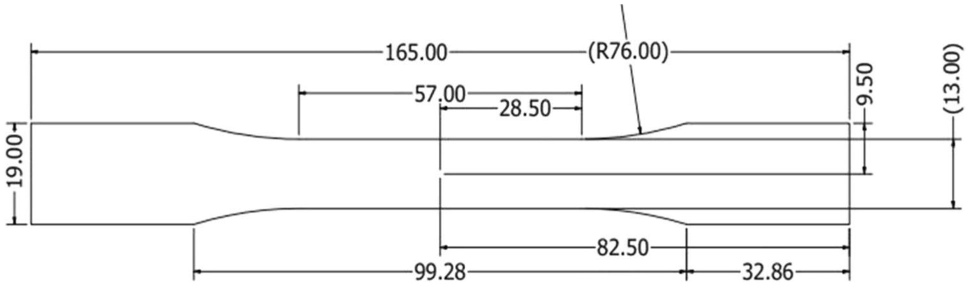
2.2.6 Surface roughness

The mean surface roughness (R_a) of the specimens was measured using a *Mitutoyo SJ-301* profilometer with a sampling length of 8 mm. The results for RPLA specimens were benchmarked with surface roughness measurements for the VPLA and IMPLA specimens. The measurements were obtained from 10 specimen points for each surface profile in order to determine consistency and standard deviation.

2.2.7 Hydraulic performance

The hydraulic performance of the impellers was tested by installing the impellers in a *Grundfos Unilift KP 250* pump to test the hydraulic performance of pumping. Figure 7 shows the water pump test rig, which was used to measure

Fig. 5 ASTM D638 Type I specimen used for tensile testing (dimensions shown in mm)



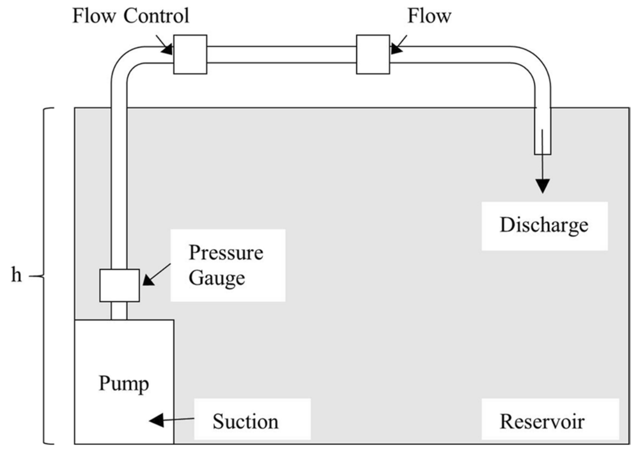


Fig. 7 Water pump test rig [26]

the parameters in Eq. 3 following the ISO 9901 standard on performance testing of pumps [42]. The pressure head (H) was obtained from the difference in heads at discharge and suction. The discharge head ($H_{\text{d, n}}$) was measured by a pressure gauge, while the suction head (H_S) was measured by the water level. The discharge flow rate ($\dot{Q}$) was calculated using a stopwatch and flow meter:

$$H = H_{d,n} - H_s \tag{3}$$

The results were plotted as H vs $\dot{Q}$ graphs in order to compare the hydraulic performance of the RPLA impeller, VPLA impeller, and the impeller from the original equipment manufacturer (OEM). The area under the H vs $\dot{Q}$ curve was used to determine the energy consumed by each impeller.

2.2.8 Surface morphology

The morphology of fracture surfaces was observed under a *ZEISS EVO 15* scanning electron microscope (SEM) under magnification ratios ranging from 50 to 250 at a voltage of 10 kV. The specimens were sputter-coated with silver (Ag) since the polymer specimen is non-conductive. The surface morphology was observed to identify defects and voids present in the 3D printed RPLA and VPLA materials. The surface of the IMPLA material was also observed for comparison.

2.3 Environmental life cycle assessment

The impellers which were found to be technically feasible were evaluated for sustainability. The first step was to assess the environmental impacts. The environmental impacts were assessed using an environmental life cycle assessment method in accordance with the ISO 14040/44 standard.

2.3.1 The goal

The goal of the study is to determine the environmental impacts of manufacturing pump impellers with RPLA and VPLA materials and their use in the industrial application of wastewater pumping with particles up to 10 mm. The functional unit (FU) is a pump impeller. The FU is used to conduct a mass balance to determine the inputs and outputs of the life cycle stages of the impeller.

2.3.2 The scope

The scope of the ELCA follows a source-to-service (S to S) approach where all the life cycle stages, from design to the delivery of service, are considered. Figure 8 presents the resource flow, which is within the scope of the ELCA.

2.3.3 Life cycle inventory

An LCI was created using the inputs and outputs of the life cycle stages, such as energy, materials, utility, labour, waste, and emission. The timeframe of the use stage was determined by the service life of each impeller. Table 5 presents the life cycle inventory developed for the functional unit.

2.3.4 Indicators and method

The *SimaPro* LCA software was used to calculate the environmental impacts of each impeller [43]. The Australian life cycle inventory database (AusLCI) in the *SimaPro* software was used to determine other inputs and outputs in the material processing and end-of-life processing stage for impact assessment. The environmental impacts that are relevant to the Australian manufacturing industry (Table 6) were determined by another consensus survey involving Australian manufacturing experts [26].

A mass manufacturing scenario in which AM machines are working 8 h per day for 5 years (lifetime of the AM machine) with an annual utilisation factor of 90% has been assumed in the calculation. Table 7 shows the production schedule with manufacturing time and batch size/production output (PO) of different manufacturing configurations of the pump impeller.

2.4 Life cycle costing (LCC)

Following the ELCA, the economic analysis was conducted to determine the unit cost of delivery of fluid during the service life of pump impellers made of RPLA and VPLA materials. A life cycle costing method was used to conduct an economic analysis using the same goal, scope, system boundary, and LCI as the ELCA, allowing ELCA and LCC results to be integrated. LCI inputs were

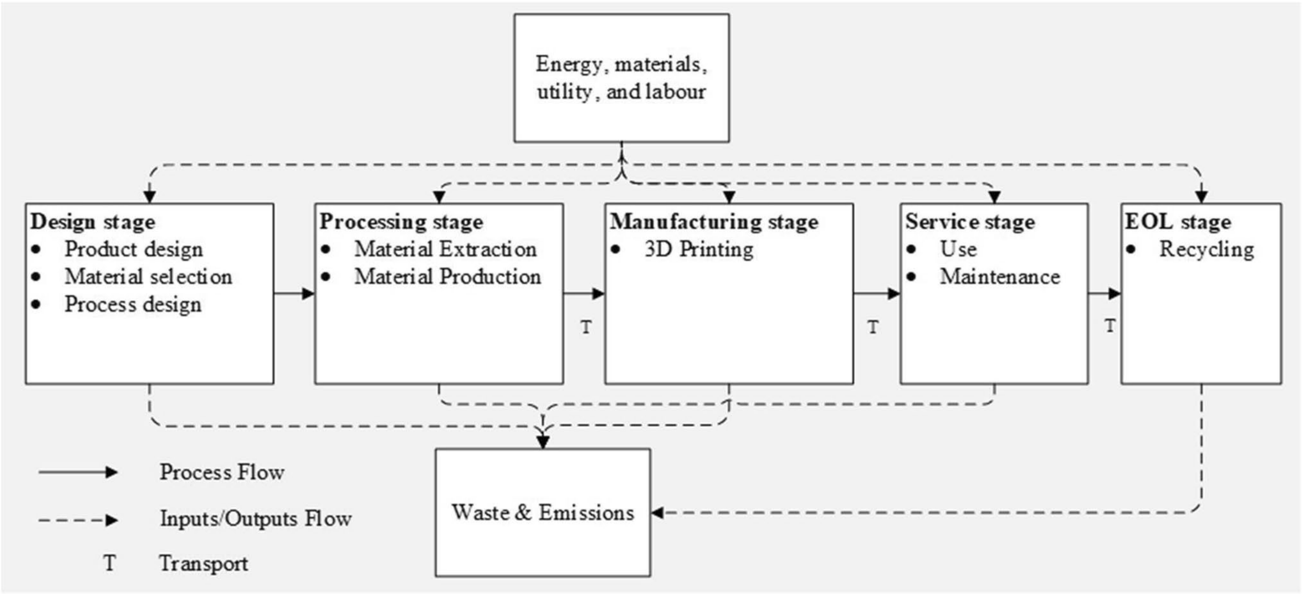


Fig. 8 The scope of ELCA [26]

Table 5 LCI of pump impellers

Stage	Material/process	RPLA	VPLA	3D printer
Design	**Energy (kWh)**			
	CAD modelling	10.00	10.00	
	Material selection	0.80	0.40	
Material processing	**Transportation (tkm)**			
	Sea			687.910
	Land	0.081	0.086	111.883
Manufacturing	**Primary materials (kg)**			
	PLA material	0.0238	0.0252	
	Material for machines (kg)			
	Steel			9.78
	Cast iron			5.87
	Aluminium			8.15
	Other plastics			6.52
	Copper			2.28
	Energy (kWh)			
	3D printing	0.717	0.659	
Use	**Energy (kWh)**			
	Use	35.45	41.14	

converted to cost values using Australia's market prices of these inputs. All cost values were inflated to the 2022 cost values using the inflation rate of Australia over 6 years. A two-step cost model was used following the methodology of Jayawardane et al. [26]. Firstly, the life cycle costs of 3D printed impellers were calculated. Secondly, the life cycle costs of pumping by 3D printed impellers were calculated.

2.4.1 LCC of impeller production

The life cycle cost of the impeller production ($LCC_{\text{impeller, prod}}$), including the life cycle stages from design to manufacturing, was determined as follows:

- Energy, utility, and labour costs in the design stage were calculated using relevant Australian energy cost figures.

Table 6 Environmental impact indicators and assessment methods

Indicator	Unit	Impact assessment method
Global warming potential (GWP)	t CO_2 eq	Australian indicator set with embodied energy V2.01
Eutrophication	kg PO_4^{3-} eq	
Land use	Ha a	
Water use	m^3 H_2O	
Cumulative energy demand (CED)	MJ	
Acidification potential	kg SO_2 eq	EPD (2013) V1.02
Abiotic depletion potential (ADP)	kg Sb eq	
Photochemical smog	kg NMVOC	ILCD 2011 midpoint + V1.08/ EU27 2010, equal weighting
Particulate matter	kg $PM_{2.5}$ eq	
Human toxicity	kg 1,4-DB eq	CML-IA baseline V3.03/EU25
Freshwater aquatic toxicity	kg 1,4-DB eq	
Marine toxicity	kg 1,4-DB eq	
Terrestrial toxicity	kg 1,4-DB eq	

CO_2 carbon dioxide, *NMVOC* non-methane volatile organic compound, *$PM_{2.5}$* particulate matter, *PO_4^{3-}* phosphate, *DB* dichlorobenzene, *Ha a.* hectare per year, *SO_2* sulphur dioxide, *Sb* antimony, *H_2O* water, *eq.* equivalent, *MJ* megajoule

Table 7 Production schedule of manufacturing scenario

	RPLA	VPLA
Total manufacturing time (h)	6.18	5.70
Batch size per annum/production output (PO)	425	461

Table 8 Capital cost and spare parts replacement costs

	3D printer (AUD)
Equipment costs[a]	9350
Transport cost	33
Extruder[a]	360
Build plate[a]	335

[a] MakerBot, USA

- Material processing costs included the raw material costs for RPLA and VPLA feedstock.
- Transportation costs were calculated from a supplier in Melbourne to a 3D printing facility in Perth.
- Manufacturing costs included the capital costs of machinery (Table 8), labour costs, and energy costs. These costs were apportioned based on the manufacturing time of each impeller (Table 7).

An inflation rate of 5.1% [44] and a discounting factor of 7% [45] were used in the LCC analysis to obtain the present value (PV) of the costs. The sum of PV was multiplied by the capital recovery factor (CRF). A CRF of 0.244 was determined by the equipment's operational time of 5 years and a discounting factor of 7%. It was then divided by the production output (PO) to obtain the $LCC_{\text{impeller, prod}}$ (Eq. 4). This cost was then converted to the price of the impeller (PI) using the value of the profit margin in the Australian pump market (35%) [46] (Eq. 5):

$$LCC_{Impeller,prod.} = (PV_{Capital} + PV_{Labour} + PV_{Energy} + PV_{O\&M}) \times CRF/PO \tag{4}$$

$$PI = LCC_{Impeller.prod.} \times (1 + PM) \tag{5}$$

2.4.2 LCC of pumping using 3D printed impellers

The service life (SL) is considered as the time period in LCC analysis. The life cycle cost of pumping using both RPLA and VPLA impellers over their SL ($LCC_{P,\,SL}$) was calculated. The fatigue life estimations of RPLA impeller and VPLA impeller were converted to SL to conduct the LCC analysis. The fatigue hours were converted to operating hours for pumping to determine the cost of energy consumed during these hours. It was considered that the pump operates for 4 h per day for 20 working days per month [47].

The energy consumed for pumping water using RPLA impeller and VPLA impeller was calculated for a fixed pressure head of 35 kPa. The energy consumption for both scenarios was multiplied by the current electricity price. The PV of energy costs over the impeller service life was then added to the PV of PI. The sum of PV was multiplied by the capital recovery factor (CRF) and divided by the service life of the impeller to obtain the $LCC_{P,\,SL}$ (Eq. 6). The study did not consider maintenance costs, and replacement costs of the pump impellers as similar costs are expected to incur in both scenarios [36]:

$$LCC_{P,SL} = \left(PV_{PI} + PV_{energy}\right) \times CRF/SL \tag{6}$$

2.5 Eco-efficiency assessment

The calculated values of life cycle costs and life cycle environmental impacts (LCEI) have been integrated using the eco-efficiency assessment framework to conduct a comparative eco-efficiency performance analysis. The following steps are used to calculate the eco-efficiency portfolio positions.

- The LCEI values are normalised by dividing with gross domestic environmental impact per inhabitant ($GDEI_i$/Inh) values (Eq. 7) to obtain the normalised environmental impacts (NEI_i) to convert all environmental impacts to the same unit [48, 49].
- The normalised values of environmental impacts were then multiplied by the corresponding weight to convert their values into one common unit, i.e. the number of Australians who produced the same amount of environmental impacts as the impeller [26]. These weights, which represent the level of importance of these environmental impacts, were ascertained by the feedback received from an expert survey [26] (also presented in the Appendix, Table 29). A single score of environmental impact (EI) was obtained by adding the normalised and weighed environmental impacts (Eq. 8):

$$NEI_i = \frac{LCEI_i}{GDEI_i/Inh} \tag{7}$$

$$EI = \sum_{i=1}^{11} NEI_i \times W_i \tag{8}$$

- The LCC values were then normalised by dividing with gross domestic product per inhabitant (GDP/Inh) value of Australia (AUD 75.250) [50] to obtain the normalised cost (NC) (Eq. 9), which is the number of Australians who produced the same GDP as the cost of the impeller [26]:

$$NC = \frac{LCC}{GDP/Inh} \tag{9}$$

- The portfolio position of environmental impact has to be determined to compare RPLA and VPLA impellers. This was done by dividing the EI of an impeller by the average value of EIs for all impellers considered for the comparative analysis. In the case of the portfolio position of cost, the NC of each impeller was divided by the average NCs of all impellers considered for this comparative eco-efficiency analysis (Eqs. 10–11) [26]:

$$PP_e = \frac{EI}{\sum EI/j} \tag{10}$$

$$PP_c = \frac{NC}{\sum NC/j} \tag{11}$$

- The environment–cost relevance ratio ($R_{E/C}$) was calculated as the ratio of mean EI and mean NC (Eq. 12), in order to determine the more influential parameter between EI and NC, which was used to determine the more influential parameter. The portfolio positions were revised (PP'_e, PP'_c) using the $R_{E/C}$ (Eqs. 13–14) and plotted in the graph of EI vs. NC (Fig. 9):

$$R_{E/C} = \frac{\sum EI_n/j}{\sum NC_n/j} \tag{12}$$

$$\mathrm{PP}'_{\mathrm{e,n}} = \frac{\left[\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j} + \left[\mathrm{PP}_{\mathrm{e,\,n}} - \left(\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j}\right)\right] \bullet \sqrt{\left(\mathrm{R}_{E/C}\right)}\right]}{\left(\sum \mathrm{PP}_{\mathrm{e,n}}\right)/\mathrm{j}} \tag{13}$$

$$\mathrm{PP}'_{\mathrm{c,n}} = \frac{\left[\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j} + \left[\mathrm{PP}_{\mathrm{c,n}} - \left(\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j}\right)\right]/\sqrt{\left(\mathrm{R}_{E/C}\right)}\right]}{\left(\sum \mathrm{PP}_{\mathrm{c,n}}\right)/\mathrm{j}} \tag{14}$$

The eco-efficiency value of a product is measured using the perpendicular distance above the diagonal line. If products are placed below the diagonal line, they are not eco-efficient and cause diagnosis, and improvement strategies should be implemented to improve the eco-efficiency. Since positions are revised with $R_{E/C}$, any changes to costs or environmental impacts of an impeller result in a change of EE portfolio positions of all impellers.

2.6 Social life cycle assessment (SLCA)

The social impacts of AM and recycled plastics for AM feedstock should be carefully assessed through several quantifiable indicators with the same goal, scope, and LCI as the ELCA and LCC. The findings of social, socio-environmental, and socio-economic aspects support the effective decision-making for the well-being of all stakeholders. The SLCA approach is a social impact assessment of the same product life cycle, which should be evaluated under the United Nations Environment Programme (UNEP) guidelines and methodological sheets for subcategories [51, 52]. The framework includes the assessment of social impacts on employees, local community, society, consumers, and other value chain actors. A quantitative approach has been used in this study using product-specific data on resource use/disposal and work hours. The social impacts on

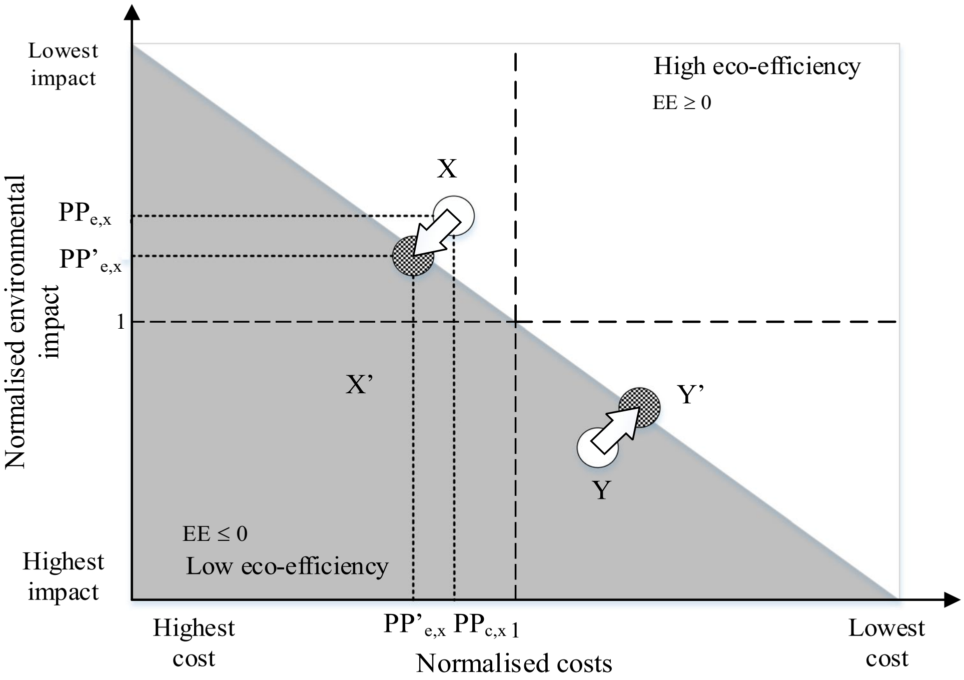


Fig. 9 EE portfolio and positions [26]

employees have been investigated under health and safety and employment level, while social impacts under local community and society have been investigated under conservation of natural resources and reduction of landfilling.

Health and safety The occupational and health hazard of AM and recycling for AM feedstock is an important indicator of social impacts on employees, which could be determined through the quantification of human toxicity potential (HTP). These include human toxicity by inhalation, ingestion, and dermal contact to employees in the mass manufacturing scenario of AM. Furthermore, plastic recycling for AM feedstock includes shredding plastic material into pellet size particles, which could lead to a higher concentration of particulate matter in manufacturing environments [33]. The method developed by Azapagic et al. [53] based on the correlation of polymer weight and HTP has been used in this study as follows (Eq. 15):

$$HTP = m_a \times TP_a \tag{15}$$

TP_a represents toxicity potentials to air, while m_a represents the mass of material emission to air. The TP_a for PLA material is 620 kg 1,4-DB eq./kg PLA. The HTP of each stage of the impeller life cycle is considered (Eq. 16) to calculate the HTP of the FU in line with the ELCA and LCC studies:

$$HTP = HTP_{Design} + HTP_{Processing} + HTP_{Mfg} + HTP_{Use} \tag{16}$$

However, the toxicity potential to the local community and society from other emissions (e.g. SO_x, NO_x, CO, $PM_{2.5}$) in the product life cycle has been quantified in the ELCA.

Employment level The level of employment was calculated (Eq. 17) from the number of hours of labour required in the mass manufacturing scenario previously considered in Sect. 2.3.4 for AM in comparison with SM/IM:

$$Employment\ level = \frac{No.\ of\ hrs.\ of\ labour\ in\ SM\ or\ IM - No.\ of\ hrs.\ of\ labour\ in\ A}{No.\ of\ hrs.\ of\ labour\ in\ SM\ or\ IM} \times 100 \tag{17}$$

Conservation of natural resources Conservation of natural resources is an intergenerational social impact indicator that affects the stakeholders of society in the SLCA model. The material and energy consumption calculations from Sect. 2.3.4 have been used to calculate the conservation of materials and conservation of energy (Eq. 18):

$$PP_e = \frac{EI}{\sum EI/j} \tag{18}$$

Reduction of landfill The waste management of plastic waste is an important social issue globally. Current waste management methods are landfilling, waste to energy, and recycling strategies.

If more industrial plastic could be recycled to manufacture feedstock material, the amount of landfill required to dispose of plastic waste could be reduced. The reduction of landfill is a social impact indicator that affects the local community. The reduction of landfill is calculated by the mass of the material that was recycled as feedstock of AM in the mass manufacturing scenario, which avoided disposal to the landfill sites. The reduction of landfill has been calculated (Eq. 19) in terms of the landfill required to carry 7000 tonnes of waste in Western Australia for 60 years [37]:

$$Reduction\ of\ landfill\ (ha) = \frac{Mass\ of\ material\ recycled}{7000\ t} \times 64\ ha \tag{19}$$

Other social impacts, including intensity of work, occupational accidents, and development of skills which have been found through literature review, have not been evaluated in this study due to the limited availability of product-specific primary data, expert judgement, and social context.

3 Results

3.1 Technical feasibility test results

The technical feasibility results of the standardised test specimens for recycled PLA (RPLA) material, virgin PLA (VPLA) material, and injection moulded PLA (IMPLA) material have been presented as follows for comparison.

Table 9 Density measurements

Material	Density
RPLA	1.09–1.14 g.cm^{-3}
VPLA	1.18 g.cm^{-3}
IMPLA	1.24 g.cm^{-3}

3.1.1 Density

The density of the material specimens is presented in Table 9. A range of densities were observed for the RPLA material, which could be due to the high level of anisotropy. Mechanical characterisation tests, such as microscopy of the fracture surfaces, were investigated to analyse the cause of these variations. Furthermore, the density of the RPLA specimens was significantly lower than the density of the VPLA and IMPLA specimens.

3.1.2 Tensile testing

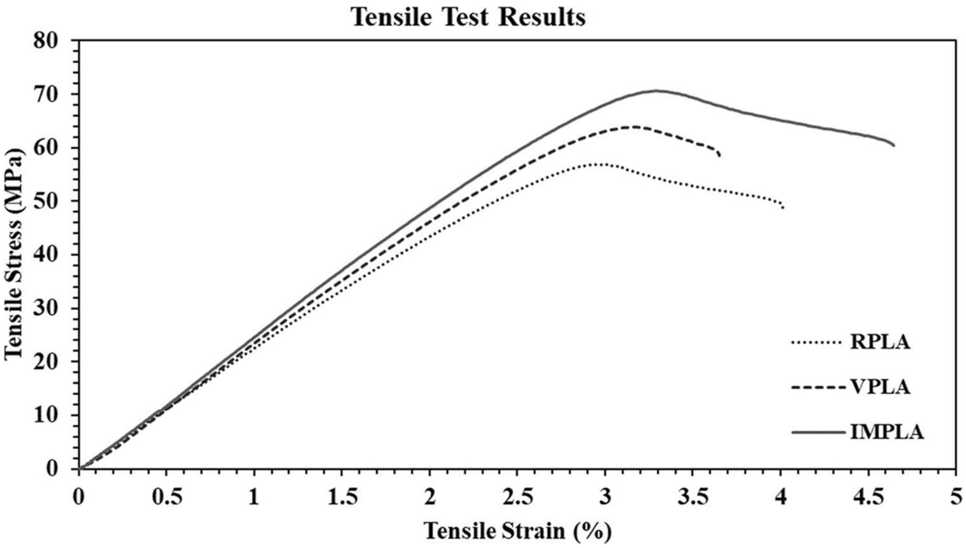
Table 10 shows the results of the tensile tests for RPLA, VPLA, and IMPLA specimens. The average ultimate tensile stress of the recycled PLA material is 12% lower than the average ultimate tensile stress of the virgin PLA material. Furthermore, the ultimate tensile stress of the 3D printed recycled PLA material is 22% lower than the virgin injection moulded PLA material. The results were similar to the findings of Zhao et al. [14] where the recycled PLA specimens showed lower tensile properties. This was attributed to the porosity present in 3D printed specimens as observed by the lower density in the RPLA and VPLA specimens. In addition, the lower density for RPLA was expected to result in higher porosity which has a negative influence on ultimate tensile stress.

Figure 10 shows the comparison of the second strongest tensile stress–strain curves of the RPLA, VPLA, and IMPLA specimens under investigation. The stress–strain curve of the IMPLA specimen exhibits the highest result, whilst the stress–strain curve of RPLA shows the lowest result. The

Table 10 Tensile test results

Material	Test No	Yield strength (MPa)	Ultimate tensile stress (MPa)	Mean of UTS (MPa)	SD of UTS	Stress @ break (MPa)	Strain @ break (%)	Elastic modulus (GPa)
RPLA	1	52.01	59.10	56.7	2.22	51.39	4.31	1.878
	2	50.47	56.96			48.36	3.89	1.807
	3	49.22	53.72			45.56	3.75	1.733
	4	51.92	57.02			49.64	4.11	1.872
VPLA	1	58.06	64.12	63.38	2.17	59.63	3.58	2.253
	2	57.32	63.45			59.01	3.42	2.168
	3	59.13	65.55			59.00	3.55	2.079
	4	53.51	60.41			56.27	3.70	2.247
IMPLA	1	67.91	70.20	70.00	1.08	60.37	4.59	2.479
	2	65.57	68.90			59.25	4.45	2.385
	3	65.94	69.49			59.76	4.49	2.287
	4	68.16	71.42			61.42	4.79	2.471

Fig. 10 Tensile test results



curves initially show similar elastic moduli for all specimens, whilst the elastic modulus of the IMPLA specimen and VPLA specimen has increased closer to the ultimate tensile stress.

Table 11 shows the integrals of each stress–strain curve up to ultimate tensile stress and final failure. The integral shows the energy absorbed by the specimen which indicates that IMPLA has the highest toughness, while the RPLA has the lowest toughness.

Table 11 Toughness results of the specimens

Material	Energy absorbed @ UTS (J.m^{-3})	Energy absorbed @ failure (J.m^{-3})
RPLA	92.01	149.65
VPLA	112.67	142.41
IMPLA	128.14	216.85

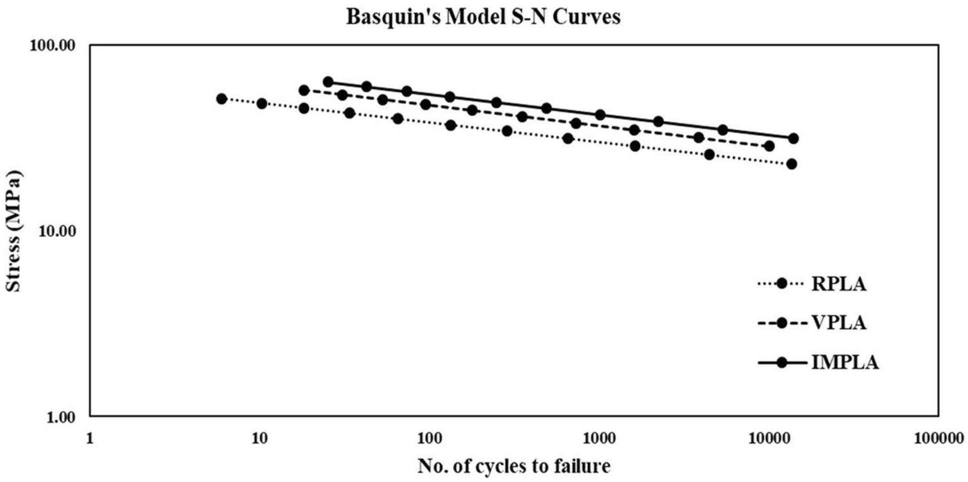
Table 12 Basquin's model values

Material	A	B
RPLA	61.98	−0.1048
VPLA	75.72	−0.1098
IMPLA	89.80	−0.1144

3.1.3 Fatigue testing

The initial stress and number of cycles to failure curves were derived from the results of the fatigue tests. The logarithmic values of the fatigue test results and the linear trend line values

Fig. 11 Basquin's model S–N curves



were incorporated into Basquin's model approximation. Table 12 shows Basquin's model values obtained from the logarithmic model, whereas Fig. 11 shows Basquin's model curves plotted for RPLA, VPLA, and IMPLA specimens from the approximation.

The order of the fatigue strength remains similar to the order of the ultimate tensile stress. The rate of decrease of fatigue strength is also the same. The fatigue life estimation of the RPLA, VPLA, and IMPLA shows that RPLA specimens have a lower fatigue life for a given tensile stress on the impeller. The reduction of the fatigue life in RPLA specimens could be due to the lower ultimate tensile stress values found from the tensile test.

Fatigue life estimation The fatigue strength values for RPLA, VPLA, and IMPLA were used for the fatigue life estimation for the centrifugal open pump impeller in the wastewater application as presented in Table 13. It was assumed that the pump is operating in a steady-state condition and that a maximum pressure load of 10 MPa is acting on the impeller vanes by the water.

The RPLA specimen and VPLA specimen both indicated an estimated fatigue life lower than the standard lifetime of a pump impeller, namely, 1600 h. Hence, the estimated fatigue life of the RPLA and VPLA specimens was considered as the service life of the impellers.

3.1.4 Dimensional tolerance

Table 14 shows the dimensional measurements of the RPLA pump impellers. The dimensions of the inner diameter of the RPLA and VPLA impellers are slightly lower than the OEM impeller, while the dimensions of the external diameter of the RPLA and VPLA impellers are slightly higher than the OEM impeller. However, all dimension measurement values are within the acceptable tolerance levels of manufacturing, fitting, and clearance of the pump impeller for the selected water pump application.

3.1.5 Hardness

Table 15 presents the hardness values of the RPLA, VPLA, and IMPLA specimens. The RPLA specimens showed the lowest hardness value (80.4), while the IMPLA specimen showed the highest hardness value (84.7). This result was attributed to the porosity and defects present in specimens during 3D printing compared to injection moulding. Furthermore, the higher standard deviation (1.582) in hardness value for RPLA could explain the inconsistency of material properties in making RPLA.

3.1.6 Surface roughness

Table 16 presents the mean surface roughness of the vane and shroud of the three RPLA impellers. The results show that the surface roughness values of the three impellers are consistent for vane and shroud surfaces. The vane surface has a higher surface roughness due to the layered surface texture in the Z direction of 3D printing.

Table 13 Summary of fatigue results

Material	Fatigue strength (MPa) @ 10^6 cycles	No. of cycles to failure @ 10 MPa	Life estimation (hours) @ 10 MPa
RPLA	14.56	3.63E+07	208.50
VPLA	17.20	1.40E+08	584.57
IMPLA	19.70	4.81E+08	-

Table 15 Hardness measurement of the PLA specimens

Material	Average hardness (D scale)	Standard deviation (D scale)
RPLA	80.4	1.582
VPLA	81.5	0.243
IMPLA	84.7	0.166

Table 14 Dimensional measurements of the RPLA pump impellers

Impeller	Inner diameter (mm)	External diameter (mm)	Vane thickness (mm)	Shroud thickness (mm)	Height (mm)
RPLA I_1	7.48	90.63	1.48	1.76	12.64
RPLA I_2	7.45	90.79	1.51	1.69	12.78
RPLA I_3	7.52	90.70	1.46	1.71	12.83
VPLA I_1	7.55	90.65	1.50	1.68	12.66
VPLA I_2	7.49	90.51	1.49	1.70	12.91
VPLA I_3	7.84	90.72	1.46	1.73	12.82
OEM	8.00	90.00	1.55	1.21	13.00
Tolerance	0.55	0.79	0.09	0.55	0.36

I_x impeller number

Table 16 Mean surface roughness (R_a) of the impellers and specimens

Specimen	Shroud surface	Vane surface	Surface
RPLA I_1	4.24 µm	8.90 µm	-
RPLA I_2	4.15 µm	8.89 µm	-
RPLA I_3	4.24 µm	9.56 µm	-
VPLA I_1	3.24 µm	8.42 µm	-
VPLA I_2	3.15 µm	8.53 µm	-
VPLA I_3	3.87 µm	8.22 µm	-
IMPLA	-	-	2.35 µm

I_x impeller number

3.1.7 Hydraulic performance

The hydraulic performance of the selected pump fitted with different pump impellers was tested in the recirculating pump test rig to measure the flow rates from shutoff to maximum flow. Table 17 presents the results of the pump performance test for RPLA impellers, VPLA impellers, and the OEM impeller. The pressure readings in the pressure gauge were converted from psi to kPa for clarity. The hydraulic performance curves (Fig. 12) were plotted using the results (Table 17).

The results show that RPLA impellers perform slightly worse than the VPLA impellers as it consumes higher power to maintain the same pressure load. However, the RPLA impellers show comparatively higher performance when compared to the stainless steel AISI 304 OEM pump impeller. This could be due to the higher density in Stainless Steel AISI 304 material of the OEM impeller, which is significantly higher than the RPLA material.

3.1.8 Surface morphology

The fracture surface micrographs of the tensile specimens are presented in Fig. 13. The fracture surface of the VPLA tensile specimen has uniform print lines and lower porosity compared to the RPLA specimen. The RPLA and VPLA specimens indicated the presence of significant voids, print lines, and porosity compared to the IPLA specimen, which has led to higher crack nucleation and propagation. The results show many commonalities to fracture surface observations of RPLA presented in other studies [14].

3.1.9 Overall technical feasibility assessment

Table 18 presents the comparison of technical properties for the RPLA, VPLA, and IMPLA specimens.

The overall technical feasibility assessment shows that the RPLA specimens have a slightly lower technical performance

Table 17 Hydraulic performance data of the impellers

Pressure head (kPa)		41.4	48.3	55.2	62.1	69.0	75.8	82.7	89.6
$\dot{Q}$ (m^3/s)	RPLA I_1	0.0021	0.0019	0.0016	0.0015	0.0011	0.0008	0.0004	
	RPLA I_2	0.0022	0.0020	0.0018	0.0016	0.0014	0.0011	0.0007	0.0002
	RPLA I_3	0.0020	0.0018	0.0015	0.0013	0.0009	0.0006	0.0004	
	VPLA I_1	0.0023	0.0021	0.0018	0.0016	0.0012	0.0009	0.0005	
	VPLA I_2	0.0023	0.0021	0.0019	0.0017	0.0015	0.0011	0.0008	
	VPLA I_3	0.0021	0.0019	0.0016	0.0013	0.0010	0.0007	0.0004	
	OEM Impeller	0.0021	0.0018	0.0014	0.0010	0.0006	0.0001		

I_x impeller number

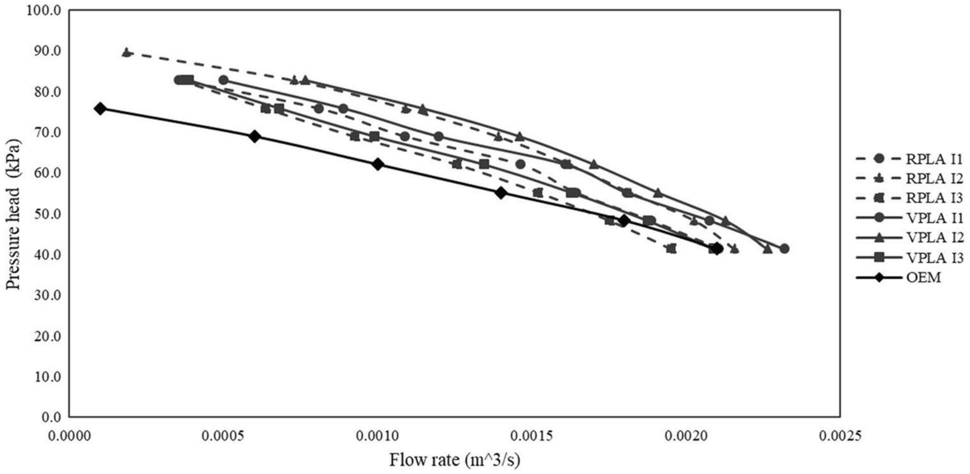


Fig. 12 Hydraulic performance (H vs $\dot{Q}$) curves of the impellers

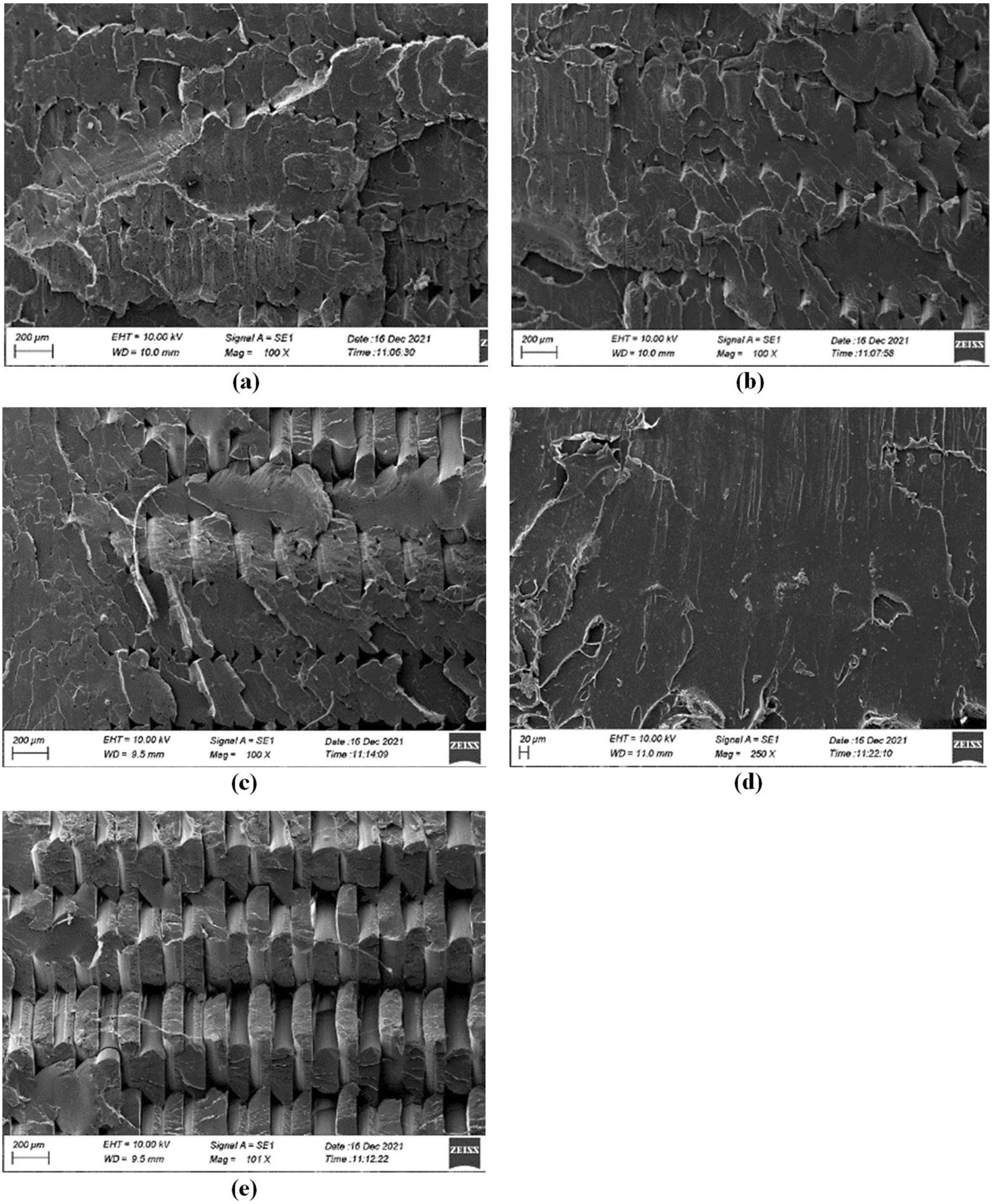


Fig. 13 Fracture surface micrographs of **a** VPLA specimen A, **b** VPLA specimen B, **c** RPLA specimen A, **d** RPLA specimen B, and **e** IMPLA specimen

Table 18 Summary of technical feasibility assessment

Parameter	RPLA	VPLA	IMPLA
Density (g.cm^{-3})	1.09–1.14	1.18	1.24
Ultimate tensile strength (mean) (MPa)	56.70	63.38	70.0
Fatigue strength @ 10^6 cycles (MPa)	14.56	17.20	19.70
Hardness (D scale)	80.4	81.5	84.7
Surface roughness (shroud/vane) (µm)	3.54/8.96	4.22/8.89	3.20/3.20

compared to VPLA and IMPLA specimens. The RPLA specimens indicate a relative density of 87.9–91.9% compared to the IMPLA material. This could be due to the increased presence of defects, porosity, and voids in the recycled material. However, the relative density of RPLA material was only slightly lower than the VPLA specimen (92.3–96.6%). The ultimate tensile strength of the RPLA material was 10.5% lower than the VPLA material and 19% lower than the IMPLA material. This could be due to the voids and high porosity contributing to crack nucleation and propagation in RPLA material. The fatigue strength of RPLA has also slightly reduced to 84.6% of the VPLA value due to the lower UTS values in the RPLA material. However, the hydraulic performance of the RPLA impellers exhibited better values compared to the OEM impeller.

Furthermore, since the material feedstock used in the RPLA specimens has been recycled, it is expected that the impact of reduced service life of these specimens could be offset by lower life cycle costs and environmental impacts. Although it will require an increased number of RPLA impellers due to the reduced service life and mechanical properties, it does not affect the pumping performance. At least the use of recycled PLA material in impeller manufacturing could reduce the PLA waste going to landfill and thereby contribute to conserving virgin resources supporting the circular economy. Therefore, the pump impellers produced by RPLA material have been considered to be technically feasible for the functional application of wastewater pumping with particles up to 10 mm.

3.2 Environmental life cycle assessment (ELCA)

The PLA feedstock material recycled from preconsumer plastic waste was found to be a feasible alternative in manufacturing 3D printed pump impellers, which reduces the virgin material consumption. Therefore, the reduction of environmental impacts from the conservation of resources and avoidance of plastic waste from end-of-life disposal should be assessed using an ELCA. Table 19 shows the total life cycle environmental impacts of RPLA and VPLA impellers for environmental performance comparison under indicators chosen in Sect. 2.3.4.

The results show that the RPLA impellers have indicated lower LCEI values for all environmental impact indicators, compared to the VPLA impellers, except for the abiotic depletion potential (ADP) which determines the level of resources extracted. Even though recycled feedstock material is used in the manufacture of RPLA impellers, multiple RPLA impellers (2.8) are required to match the service life of a single VPLA impeller, which increases the ADP of RPLA impellers by 17.9%. The network chart as presented in Fig. 14 shows that 79% of ADP of RPLA impellers have been attributed to the manufacturing stage, while 19.1% have been attributed to the material extraction stage.

Table 19 Breakdown of LCEI based on indicators

Impact category	Unit	Total LCEI		Variance
		RPLA	VPLA	
GWP[a]	kg CO_2 eq	3.4650	119.9354	−97.1%
Eutrophication[a]	kg PO^{4---} eq	0.0014	0.0472	−97.0%
Land use[a]	Ha. A	0.0000	0.0006	−96.8%
Water use[a]	m^3 H_2O	0.0096	0.1984	−95.1%
Energy consumption[a]	kWh	0.2316	2.5729	−91.0%
Acidification potential[b]	kg SO_2 eq	0.0083	0.2728	−97.0%
Abiotic depletion potential[b]	kg Sb eq	2.68E-06	2.27E-06	+17.9%
Human toxicity[c]	kg 1,4-DB eq	0.3108	8.1443	−96.2%
Freshwater toxicity[c]	kg 1,4-DB eq	0.1002	2.1742	−95.4%
Marine toxicity[c]	kg 1,4-DB eq	330.7713	7170.4679	−95.4%
Terrestrial toxicity[c]	kg 1,4-DB eq	0.0048	0.1566	−97.0%
Photochemical smog[d]	kg NMVOC eq	0.0117	0.3901	−97.0%
Particulate matter[d]	kg PM 2.5 eq	0.0010	0.0346	−97.2%

[a] Australian indicator set with embodied energy V2.01, [b] EPD (2013) V1.02, [c] ILCD 2011 midpoint + V1.08/EU27 2010, equal weighting, [d] CML-IA baseline V3.03/EU25

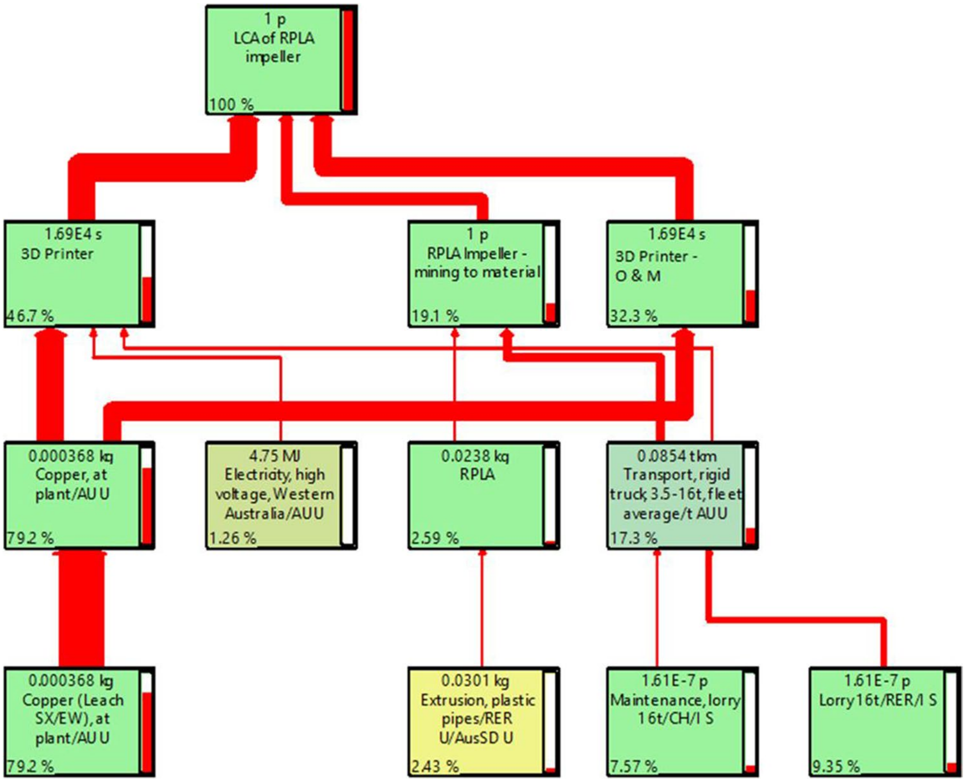


Fig. 14 Network chart for ADP of RPLA impeller

The energy consumption of each RPLA impeller also accounts for a 91% reduction compared to the VPLA impeller. However, the emissions from energy consumption from fossil fuel sources have contributed significantly to other environmental impacts. The global warming potential (GWP) has significantly reduced by 97.1% due to the replacement of the VPLA impeller by RPLA impeller. Figure 15 shows the network chart for GWP, which is significantly attributed to the energy consumption in the design stage and manufacturing stage, where the electricity is predominantly produced from black coal and natural gas. The highest environmental impact reduction was observed in particulate matter (97.2%), while the lowest reduction was observed in water use (95.1%). Even though the RPLA impeller has exhibited lower service life compared to the VPLA impeller, the environmental impacts have been significantly reduced due to the use of recycled materials.

After the evaluation of environmental impacts, economic impacts should be investigated since environmentally friendly technologies are not always economically viable.

3.3 Life cycle costing (LCC)

Table 20 shows the price of the impeller (PI) for the RPLA and VPLA cases. The use of recycled materials has significantly reduced the cost of feedstock material for AM. However, the higher production output (PO) of VPLA impellers due to lower printing time has resulted in a lower PI (7.85%) for VPLA impellers.

The $PV_{\text{total, p}}$ value of RPLA and VPLA impellers was calculated from the PV of capital cost and the PV of utility costs (Table 21).

The fatigue life estimations of 208.5 h for the RPLA impeller and 584.6 h for the VPLA impeller were converted to SL to conduct the LCC analysis. Accordingly, a pump using a RPLA impeller can operate for 2 months and 12 days, whereas a pump using a VPLA impeller can operate for 7 months and 6 days. It was estimated that 3 RPLA impellers were needed to meet the SL of one VPLA impeller. This was incorporated into the capital cost calculation of the service stage. The VPLA impeller shows a lower energy consumption (5.13%) in the use stage, when compared to the RPLA impeller, due to the lower surface roughness of the VPLA impellers resulting in higher hydraulic efficiency. The lower service life of the RPLA impeller has resulted in higher $\mathrm{PV}_{\text{total, p}}$ due to the higher capital cost (3.24 times). The $\mathrm{LCC}_{\text{P, SL}}$ of the VPLA and RPLA pump impellers are presented in Table 22.

The total life cycle cost of the RPLA impeller is significantly higher than the total life cycle cost of the VPLA impeller, due to higher pumping costs and lower service life of the 100% RPLA impeller. The durability and service life of the RPLA impellers could be further improved by blending RPLA material with virgin material, e.g. 50% wt. RPLA [14]. The addition of fillers and reinforcement fibre material [26] to the blend could also further reduce the life cycle cost of the RPLA impellers and make them cost-competitive with the VPLA impellers.

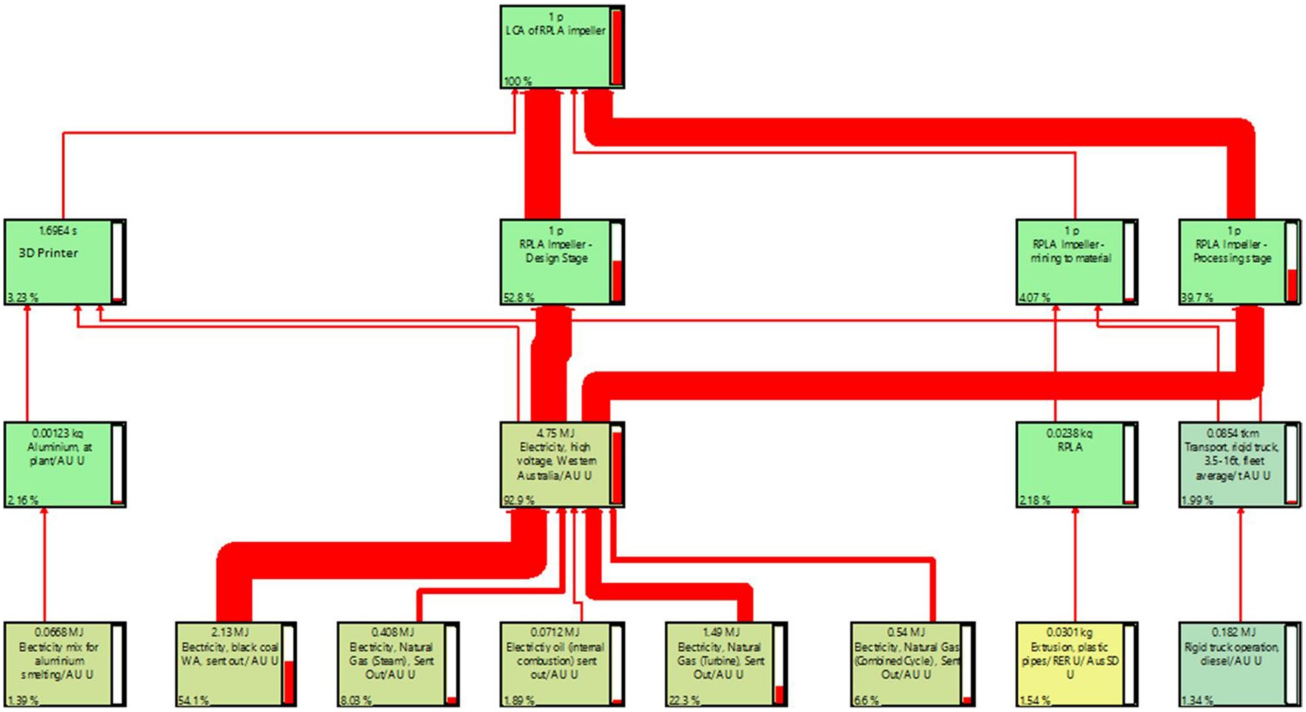


Fig. 15 Network chart for GWP of RPLA impeller

Table 20 Price of the impeller

	$PV_{\text{total, prod.}}$ (AUD)	Annuitised cost (AUD)	PO	$\text{LCC}_{\text{impeller, prod}}$ (AUD)	PI (AUD)
RPLA	12,821.04	3126.93	425	7.35	9.93
VPLA	12,808.17	3123.79	461	6.78	9.15

Table 21 Present values of the pump usage costs

Month	RPLA impeller		VPLA impeller	
	Capital cost (AUD)	Utility cost (AUD)	Capital cost (AUD)	Utility cost (AUD)
0	9.93	-	9.15	-
1		7.58	-	7.19
2	-	7.56	-	7.18
3	9.88	7.55	-	7.16
4	-	7.54	-	7.15
5	-	7.53	-	7.14
6	9.84	7.52	-	7.13
7	-	7.50	-	7.12
8	-	7.49	-	7.11
Total	29.65	60.27	9.15	57.18
$PV_{\text{total, p}}$	89.92		66.33	

Table 22 Life cycle cost of pump usage

	$PV_{\text{total, P}}$ (AUD)	Annuitised cost (AUD)	$\text{LCC}_{\text{P, SL}}$ (AUD)
RPLA	89.92	148.51	685.45
VPLA	66.33	109.55	180.09

3.4 Eco-efficiency assessment (EEA)

Whilst RPLA impellers offer significant environmental benefits compared to VPLA impellers, the economic assessment showed that the costs of impellers using recycled material are slightly higher than those made from virgin materials. Further analysis is required to investigate the environmental impacts per dollar invested in each manufacturing strategy in order to ascertain options that balance both economic and environmental objectives. As a result, an eco-efficiency analysis was performed to determine the eco-efficiency of RPLA and VPLA impellers. Table 23 shows the normalised environmental impacts (NEI) of RPLA and VPLA impellers over their service life in terms of inhabitants per functional unit of pump impeller delivering fluid. The RPLA impeller showed 93% lower normalised environmental impact when compared to the VPLA impeller.

Several environmental impacts were found to be the dominant contributors to the NEI. The energy consumption per

Table 23 Normalised environmental impacts in terms of number of inhabitants per FU (FU, a pump impeller delivering fluid over service life)

	RPLA impeller		% contribution				VPLA impeller		% contribution			
Indicator	EI	TC	DC	MPC	MfgC	UC	EI	TC	DC	MPC	MfgC	UC
GWP	1.38E-08	2.74	52.8	4.1	43.0	0.1	4.78E-07	6.37	16.2	23.0	60.7	0.1
Eutrophication	7.19E-09	1.43	49.9	8.5	41.4	0.2	2.36E-07	3.15	9.0	56.5	34.3	0.2
Land use	6.34E-11	0.01	46.9	16.1	37.0	0.1	1.96E-09	0.03	7.4	65.6	26.9	0.1
Water use	1.14E-09	0.23	31.2	25.8	42.7	0.3	2.34E-08	0.31	7.3	46.3	46.1	0.4
Energy consumption	3.83E-07	76.1	42.7	4.4	52.8	0.1	4.27E-06	56.8	15.9	46.3	59.6	0.2
AP	5.62E-09	1.11	50.4	6.6	42.8	0.2	1.86E-07	2.48	14.8	26.8	58.1	0.3
ADP	8.79E-13	0.00	0.7	19.1	79.5	0.7	7.47E-13	0.00	0.1	30.3	68.9	0.7
Human toxicity	9.73E-09	1.93	39.7	22.7	36.9	0.7	2.55E-07	3.40	7.6	59.2	32.5	0.7
Freshwater ET	5.86E-08	11.6	32.4	35.2	31.4	1.0	1.27E-06	16.96	4.0	77.6	17.8	0.6
Marine ET	2.75E-09	0.54	32.5	33.5	33.0	1.0	5.96E-08	0.79	4.6	73.1	21.5	0.7
Terrestrial ET	5.46E-09	1.08	49.7	11.5	38.7	0.2	1.79E-07	2.39	7.6	65.0	27.3	0.1
PS	1.41E-08	2.79	51.0	6.6	42.3	0.1	4.71E-07	6.27	16.0	22.6	61.2	0.3
Particulate matter	2.28E-09	0.45	53.6	3.7	42.6	0.1	8.02E-08	1.07	18.3	14.6	67.0	0.2
Total	5.04E-07						7.51E-06					

EI environmental impact, *TC* total contribution, *Des* design stage contribution, *MPC* material processing stage contribution, *MfgC* manufacturing stage contribution, *UC* use stage contribution, *GWP* global warming potential, *ADP* abiotic depletion potential, *ET* eco-toxicity, *AP* acidification potential, *PS* photochemical smog

pump impeller showed the highest contribution (76.1% for RPLA and 56.8% for VPLA) to the NEI in both scenarios. This could be due to high energy consumption in the manufacturing stage (52.8% RPLA and 59.6% VLPA). In addition, the design stage energy consumption of RPLA impeller (42.7%) also significantly contributed to the total energy consumption. This could be due to the higher process design time when dealing with recycled feedstock material. The material processing stage (46.3%) contributed significantly to the energy consumption of the VPLA impeller. This could be due to high energy consumption in virgin material feedstock production.

The next significant environmental impact was identified as freshwater eco-toxicity, which contributes 11.6% to the NEI of the RPLA impeller and 16.96% to the NEI of VPLA impeller. The material processing stage showed the highest contribution to the freshwater eco-toxicity (35.2% for RPLA and 77.2% for VPLA). The photochemical smog (2.79% for RPLA and 6.27% for VPLA) and GWP (2.74% for RPLA and 6.37% for VPLA) were found to be other significant contributors to the NEI. The manufacturing stage of 3D printing had significantly contributed to the photochemical smog (42.3% for RPLA and 61.2% for VPLA) and GWP (43.0% for RPLA and 60.7% for VPLA).

The abiotic depletion values observed for the RPLA impeller were lower than that of the VPLA impeller, but the contribution of this impact to the NEI was not significant. The level of contribution not only depends on the life cycle inputs but also on the weights assigned by the experts on relevance to manufacturing in Australia. The sum of normalised environmental impacts was used with normalised costs for the eco-efficiency assessment to determine the environmentally friendly option not entailing excessive costs.

Table 24 presents the overall normalised costs and normalised environmental impacts of the RPLA and VPLA impellers in terms of Australian inhabitants. These values were calculated according to Eqs. 7–9.

The results show that the normalised environmental impact of AM decreased from 7.51E-06 to 5.04E-07 inhabitant equivalents, i.e. 93% lower, by replacing virgin material with recycled material. However, the normalised cost of the AM process has increased the GDP produced by 2.56E-03 inhabitants per year to 9.748E-03 inhabitants per year, which is 74% higher than when using virgin material for AM. These values must be integrated by conducting an eco-efficiency assessment, to determine the environmental impact per dollar invested in recycling.

3.4.1 Eco-efficiency portfolio analysis

The initial eco-efficiency portfolio positions were determined using normalised environmental impacts and normalised costs. The calculated RE/C value of 0.001 indicates that costs

Table 24 Normalised costs and normalised environmental impact of impellers

Configuration	EIn (inhabitants)	NCn (inhabitants)
RPLA	5.04E-07	9.74E-03
VPLA	7.51E-06	2.56E-03

outweigh environmental impacts. Table 25 displays the portfolio positions. These portfolio positions are depicted in Fig. 16 as a graph of normalised environmental impact vs normalised cost.

The portfolio analysis showed that the RPLA impeller was placed above the diagonal, whereas the VPLA impeller was placed below the diagonal. This infers that the RPLA impeller is eco-efficient, while the VPLA impeller is not eco-efficient. The lower normalised environmental impact (93%) of the RPLA impeller compared to VPLA impeller has offset the higher normalised costs of the RPLA impeller (74%) compared to the VPLA impeller. It is evident that the recycling of plastic material for AM reduces the environmental impacts of additive manufacturing significantly for each dollar invested in recycling by 93%. Even though recycled material entails significantly higher costs than virgin material (74%), the potential for environmental impact reduction by recycling is significantly higher than for other resource recovery methods.

The normalised costs and cumulative energy demand of the RPLA impeller, which also accounts for a significant portion of normalised environmental impacts, could be further reduced by using renewable energy for operating these AM pump impellers.

3.5 Social impact assessment

The social impacts affecting the employee stakeholders of a company (mass manufacturing pump impellers using additive manufacturing) have been evaluated as follows using the product-specific primary data in terms of resource use and working hours.

3.5.1 Health and safety

The occupational health and safety of employees are an important consideration in the manufacturing industry. In mass manufacturing scenarios using AM, it was reported that non-fatal accidents, such as minor cuts, occurred when removing parts from the print bed and also for removing support structures in some AM processes [35]. However, AM has eliminated fatal accidents in manufacturing by reducing human–machine interactions and eliminating cutting tools and fixtures in conventional subtractive manufacturing [33]. Table 26 presents the HTP values of the RPLA and VPLA impellers. The results indicated that the RPLA impeller reduces the HTP by reducing the emission of PLA materials into air during the AM process.

The reduction of HTP, and other fatal and non-fatal accidents through AM, could also result in positive economic impacts as they lower the costs of compensation and health, avoid downtime, and improve productivity.

Table 25 Portfolio positions of pump impellers

Impeller	PPe	PPc	PP'e	PP'c
AM	0.0563	1.5839	0.7680	1.1436
SM	1.9437	0.4161	1.2320	0.8564

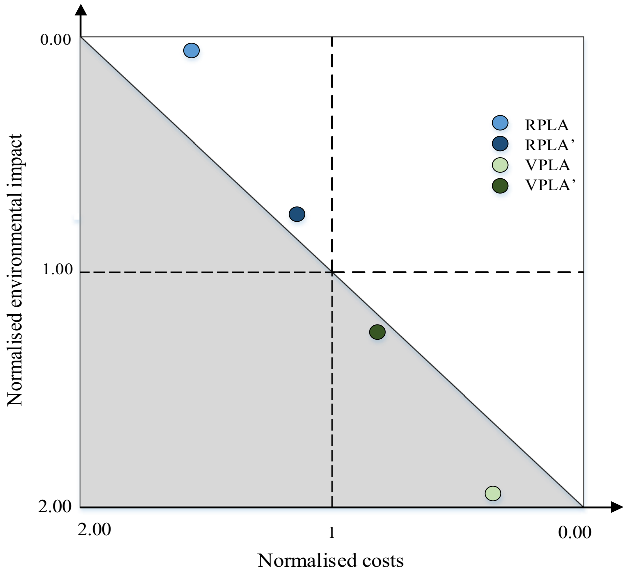


Fig. 16 Eco-efficiency portfolio (RPLA, portfolio position of RPLA impeller; VPLA, portfolio position of VPLA impeller; RPLA', revised portfolio position of RPLA impeller; SM', revised portfolio position of VPLA impeller)

3.5.2 Employment level

The employment level changes for the same product when using different manufacturing strategies. AM reduces the labour hours in manufacturing time for setup/configuration, repair, and monitoring. Table 27 shows the calculation of changes to the level of employment in mass manufacturing scenarios under different manufacturing strategies. The results show that the level of employment is reduced when AM is replaced by IM and SM. The reduction of jobs in manufacturing VPLA impellers is higher compared to that of RPLA impellers as the latter involves more person-hours to sort out any expected difficulties in setup/configuration, repair, and monitoring of equipment with recycled material feedstock.

There are socio-economic implications of the production of AM impellers in terms of employment, which could

Table 26 HTP calculation

Parameter	RPLA	VPLA
Mass of impeller (kg)	0.0238	0.0252
Filament volume (cm^3)	21.0	21.5
Density (g.cm^{-3})	1.14	1.18
Mass of material used (filament volume × density) (kg)	0.02394	0.02537
Mass emission	0.00014	0.00017
HTP	0.0868	0.1054

Table 27 Employment levels

Parameter	RPLA	VPLA	IMPLA	SM
No. of hours of labour for FU	0.618	0.57	0.84[a]	2.24[a]
Reduction from IM	26.4%	43.0%	-	-
Reduction from SM	72.4%	74.6%	-	-

[a] [26]

Table 28 Conservation of natural resources

Parameter	RPLA	VPLA	IMPLA	SM
Primary material for FU (kg)	0.0238	0.0252	0.0273[a]	0.3161[a]
Reduction from IM	12.8%	7.7%	-	-
Reduction from SM	92.5%	92.0%	-	-

[a] [26]

potentially be overcome through mass manufacturing that involves a highly skilled workforce.

The social impacts affecting the stakeholders, including the local community and society, have been evaluated as follows in terms of the conservation of natural resources and reduction of landfill. The data specific to each impeller have been used in the calculation of resource use and disposal in mass manufacturing scenario.

3.5.3 Conservation of natural resources

The conservation of natural resources has been investigated with the intensity of primary materials used in different manufacturing strategies in the mass manufacturing scenario.

The results in Table 28 show that the RPLA impeller reduces the material consumption by 12.8% compared to IMPLA impellers and 92.5% compared to SM impellers. The VPLA impeller reduces the material consumption by 7.7% compared to IMPLA and 92.0% compared to SM. This demonstrates that AM and material recycling could significantly reduce virgin PLA production, easing the burden on food production, i.e. sugar cane and corn starch.

Approximately 91% of the energy consumption can be reduced by replacing VPLA impellers with RPLA impellers for production, resulting in the conservation of resources for future generations, and thereby enhancing intragenerational social equity.

3.5.4 Reduction of landfill

The recycled PLA material used in mass manufacturing of RPLA impellers amounts to 101.2 kg per annum. Therefore, 9.25E-04 ha of landfill could be reduced from an industrial manufacturer mass manufacturing pump impellers with one 3D printer. The ELCA of the study also showed a reduction of land use by 96.8% by an RPLA impeller compared to a VPLA impeller. The diversion of waste PLA to 3D printing applications not only reduces toxins and leachate from landfill, but also reduces landfill area.

4 Conclusions and recommendations

The technical feasibility assessment evaluated the durability and service life of the RPLA and VPLA impellers. The estimated service life of the RPLA impeller was significantly reduced due to its lower density, ultimate tensile strength, and fatigue strength compared to the VPLA material. However, the RPLA impeller exhibited higher hydraulic performance compared to the original component in the hydraulic performance test. The RPLA impeller was deemed technically feasible since it exhibits higher pumping performance which was not affected by the reduced service life and mechanical properties.

The ELCA results showed that the RPLA impeller creates significantly lower environmental impacts compared to the VPLA impeller (93%). However, the life cycle costs of the RPLA impeller were significantly higher (74%) due to its lower service life compared to the VPLA impeller and its higher energy consumption in pump usage. The eco-efficiency assessment revealed that recycled materials significantly improve eco-efficiency performance. The social impact assessment revealed positive social impacts from additive manufacturing for employees in terms of health and safety. The employment levels of AM have reduced compared to SM due to high machine automation in AM, while opportunities for high-skilled employment and mass additive manufacturing have increased. The replacement of VPLA with an RPLA impeller could strengthen food security by conserving natural resources, including land and crops. The study found that the use of recycled material in AM is more techno-eco-efficient than the use of virgin materials and increases the waste diversion rate.

The techno-eco-efficiency assessment in this study was limited to the PLA material. The techno-eco-efficiency of recycling other common filament feedstock such as ABS, PET, and nylon could be further explored in future research. However, the results might be expected to vary due to the effects of viscosity and hygroscopic properties of different recycled materials [14]. As recycled PLA has lower technical performance properties when compared to virgin PLA, blends of recycled virgin materials (20% wt., 30% wt., and 50% wt.), fillers, and reinforcement fibres could be further investigated to improve technical performance and the resulting service life of the impellers. Furthermore, the benefits of using renewable energy sources for the production of manufacturing parts using recycled materials could also be investigated. In addition, the SLCA in this study could be further extended in future research using a reference scale approach to assess qualitative indicators, such as fair wages, employment relationships, social responsibility parameters, local employment opportunities, commitment to sustainability management and product performance, and end-of-life waste management responsibilities.

Appendix

Table 29 Factors for normalisation and weighing of the environmental impacts [26]

Environment impacts (EIs)	$GDEI_i$	Unit (per inhabitant/y)	Weight (Wi)
Global warming potential (GWP)	28,690	t CO_2 eq	11.44%
Photochemical smog	75	kg NMVOC	9.06%
Particulate matter	45	kg $PM_{2.5}$ eq	10.42%
Eutrophication	19	kg PO_4^{3-} eq	9.51%
Human	3216	kg 1,4-DB eq	10.08%
Terrestrial	88	kg 1,4-DB eq	10.08%
Freshwater	172	kg 1,4-DB eq	10.08%
Marine	12,117,106	kg 1,4-DB eq	10.08%
Land use	26	Ha a	8.83%
Acidification potential	123	kg SO_2 eq	8.38%
Abiotic depletion potential (ADP)	300	kg Sb eq	9.85%
Water use	930	m^3 H_2O	10.99%
Cumulative energy demand (CED)	246,900	MJ	11.44%

CO_2carbon dioxide, *NMVOC* non-methane volatile organic compound, $PM_{2.5}$ particulate matter, PO_4^{3-} phosphate, *DB* dichlorobenzene, *Ha a.* hectare per year, SO_2 sulphur dioxide, *Sb* antimony, H_2O water, *eq.* equivalent, *MJ* megajoule

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Author contribution All authors contributed to the conceptualisation and methodology. Analysis; investigation; data curation; writing, original draft; and visualisation were performed by H.J. All authors contributed to writing, review and editing. All authors read and approved the final manuscript.

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The research data and material will be made available at Curtin Research Data Collection.

Declarations

Ethics approval The ethics approval for this research work was obtained from Curtin University under approval number HRE2020-0203.

Conflict of interest The authors declare no competing interests.

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APPENDIX E – ETHICS APPROVAL

Curtin University

Research Office at Curtin

GPO Box U1987
Perth Western Australia 6845

Telephone +61 8 9266 7863
Facsimile +61 8 9266 3793
Web research.curtin.edu.au

07-May-2020

Name:	Wahidul Biswas
Department/School:	Sustainable Engineering Group
Email:	W.Biswas@curtin.edu.au

Dear Wahidul Biswas

RE: Ethics Office approval
Approval number: HRE2020-0203

Thank you for submitting your application to the Human Research Ethics Office for the project **'Eco-efficiency Performance Comparison of Additive and Subtractive Manufactured Parts**.

Your application was reviewed through the Curtin University Negligible risk review process.

The review outcome is: **Approved**.

Your proposal meets the requirements described in the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research (2007).*

Approval is granted for a period of one year from **07-May-2020** to **06-May-2021**. Continuation of approval will be granted on an annual basis following submission of an annual report.

Personnel authorised to work on this project:

Name	Role
Wijerathne Jayawardane, Heshan Thenuka	Student
Biswas, Wahidul	CI

Approved documents:

Document

Standard conditions of approval

1. Research must be conducted according to the approved proposal
2. Report in a timely manner anything that might warrant review of ethical approval of the project including:
    - proposed changes to the approved proposal or conduct of the study
    - unanticipated problems that might affect continued ethical acceptability of the project
    - major deviations from the approved proposal and/or regulatory guidelines
    - serious adverse events
3. Amendments to the proposal must be approved by the Human Research Ethics Office before they are implemented (except where an amendment is undertaken to eliminate an immediate risk to participants)
4. An annual progress report must be submitted to the Human Research Ethics Office on or before the anniversary of approval and a completion

report submitted on completion of the project

5. Personnel working on this project must be adequately qualified by education, training and experience for their role, or supervised
6. Personnel must disclose any actual or potential conflicts of interest, including any financial or other interest or affiliation, that bears on this project
7. Changes to personnel working on this project must be reported to the Human Research Ethics Office
8. Data and primary materials must be retained and stored in accordance with the Western Australian University Sector Disposal Authority (WAUSDA) and the Curtin University Research Data and Primary Materials policy
9. Where practicable, results of the research should be made available to the research participants in a timely and clear manner
10. Unless prohibited by contractual obligations, results of the research should be disseminated in a manner that will allow public scrutiny; the Human Research Ethics Office must be informed of any constraints on publication
11. Approval is dependent upon ongoing compliance of the research with the Australian Code for the Responsible Conduct of Research, the National Statement on Ethical Conduct in Human Research, applicable legal requirements, and with Curtin University policies, procedures and governance requirements
12. The Human Research Ethics Office may conduct audits on a portion of approved projects.

Special Conditions of Approval

Condition of Approval.

It is the responsibility of the Chief Investigator to ensure that any activity undertaken under this project adheres to the latest available advice from the Government or the University regarding COVID-19.

This letter constitutes low risk/negligible risk approval only. This project may not proceed until you have met all of the Curtin University research governance requirements.

Should you have any queries regarding consideration of your project, please contact the Ethics Support Officer for your faculty or the Ethics Office at hrec@curtin.edu.au or on 9266 2784.

Yours sincerely

Amy Bowater
Ethics, Team Lead

APPENDIX F – PERMISSION STATEMENTS

Decision on submission to Sustainable Manufacturing and Service Economics

em.smse.874.82affc.0293db3c@editorialmanager.com
<em.smse.874.82affc.0293db3c@editorialmanager.com>
on behalf of
Bin Shen <em@editorialmanager.com>
Sat 15/04/2023 3:02 PM
To: Heshan Thenuka Wijerathne Jayawardane <h.wijerath@postgrad.curtin.edu.au>

Manuscript Number: SMSE-D-22-00010R2

Sustainability Perspectives – A Review of Additive and Subtractive Manufacturing

Dear Mr. Jayawardane,

Thank you for submitting your manuscript to Sustainable Manufacturing and Service Economics.

I am pleased to inform you that your manuscript has been accepted for publication.

My comments, and any reviewer comments, are below.

Your accepted manuscript will now be transferred to our production department. We will create a proof which you will be asked to check, and you will also be asked to complete a number of online forms required for publication. If we need additional information from you during the production process, we will contact you directly.

We appreciate you submitting your manuscript to Sustainable Manufacturing and Service Economics and hope you will consider us again for future submissions.

We encourage authors of original research papers to share the research objects – including raw data, methods, protocols, software, hardware and other outputs – associated with their paper. More information on how our open access Research Elements journals can help you do this is available at https://www.elsevier.com/authors/tools-and-resources/research-elements-journals?dgcid=ec_em_research_elements_email.

Kind regards,
Bin Shen, Ph.D.
Associate Editor
Sustainable Manufacturing and Service Economics

Editor and Reviewer comments:

The paper is acceptable for publication.

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Cc: Wahidul Biswas <W.Biswas@curtin.edu.au>;Heshan Thenuka Wijerathne Jayawardane <h.wijerath@postgrad.curtin.edu.au>

Great!

Thank you so much, Richard.

Jawa

****

Dr. I. S. Jawahir
James F. Hardymon Chair in Manufacturing Systems,
Professor of Mechanical Engineering, and
Director of Institute for Sustainable Manufacturing (ISM)
414B, CRMS Building
University of Kentucky
Lexington, KY 40506
U.S.A.

Phone: (859) 323-3239
Fax: (859) 257-1071
E-mail: is.jawahir@uky.edu
Website: http://www.engr.uky.edu/ism/

****

From: Richard Sharp <sharp_richard@btconnect.com>
Sent: Wednesday, April 12, 2023 11:36 AM
To: Jawahir, Ibrahim S. <is.jawahir@uky.edu>
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Dear Jawa

Yes, that’s fine, provided suitable acknowledgement is given.

Best wishes

Dick Sharp
Journal manager, IJSM

From: Jawahir, Ibrahim S. <is.jawahir@uky.edu>
Sent: 12 April 2023 06:06
To: Julie Mcallister <Julie@inderscience.com>
Cc: A/Prof Wahidul Biswas <W.Biswas@curtin.edu.au>; Heshan Thenuka Wijerathne Jayawardane <h.wijerath@postgrad.curtin.edu.au>
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Dear Ms. Julie McAllister,

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Can you please quickly review this request and approve the request as early as possible? I must tell you that it is a common practice for such material to be included in the unpublished PhD work, and many journals allow this. There is a deadline for the submission of PhD draft to the university by the end of this week. Therefore, I would appreciate your prompt response.

Thanks and with best wishes.

Jawa
I.S. Jawahir
Editor-in-Chief, IJSM

****

Dr. I. S. Jawahir
James F. Hardymon Chair in Manufacturing Systems,
Professor of Mechanical Engineering, and
Director of Institute for Sustainable Manufacturing (ISM)
414B, CRMS Building
University of Kentucky
Lexington, KY 40506
U.S.A.

Phone: (859) 323-3239
Fax: (859) 257-1071
E-mail: is.jawahir@uky.edu
Website: http://www.engr.uky.edu/ism/

****

From: Wahidul Biswas <W.Biswas@curtin.edu.au>
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CAUTION: **External Sender**

Dear Prof Jawahir,
Hope you are well.
The article titled 'Techno-eco-efficiency' performance of 3D printed impellers: an application of life cycle assessment' (https://doi.org/10.1504/IJSM.2021.116871) was published in the International Journal of Sustainable Manufacturing. The journal publisher's permission was sought for inclusion of this paper as a thesis chapter in Heshan's PhD thesis.
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With best regards
Wahidul Biswas
Curtin University

From: Heshan Thenuka Wijerathne Jayawardane <h.wijerath@postgrad.curtin.edu.au>
Sent: Monday, March 27, 2023 9:02:17 AM
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Heshan

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This work was completed as a part of my PhD study. I kindly request your permission to reproduce this article in my PhD thesis.

Looking forward to hearing from you.

Best regards,
Heshan Jayawardane
BScEng (Hons), GradIEAust, AMIESL
Student ID:19914255
Tel | +61 4 8195 1156
Email | h.wijerath@postgrad.curtin.edu.au
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Title	Eco-efficiency Performance Comparison of Additive and Subtractive Manufactured Parts	**Institution Name**	Curtin University, Australia
		Expected Presentation Date	2023-03-31
Instructor Name	Wahidul K. Biswas		

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The Requesting Person/Organization to Appear on the License	Heshan Jayawardane

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Editor of Portion(s)	Jayawardane, Heshan; Davies, Ian J.; Gamage, J. R.; John, Michele; Biswas, Wahidul K.	**Author of Portion(s)**	Jayawardane, Heshan; Davies, Ian J.; Gamage, J. R.; John, Michele; Biswas, Wahidul K.
Volume of Serial or Monograph	121	**Publication Date of Portion**	2022-08-01
Page or Page Range of Portion	6811-6836		

RIGHTSHOLDER TERMS AND CONDITIONS

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Marketplace Permissions General Terms and Conditions

The following terms and conditions ("General Terms"), together with any applicable Publisher Terms and Conditions, govern User's use of Works pursuant to the Licenses granted by Copyright Clearance Center, Inc. ("CCC") on behalf of the applicable Rightsholders of such Works through CCC's applicable Marketplace transactional licensing services (each, a "Service").

1) **Definitions.** For purposes of these General Terms, the following definitions apply:

"License" is the licensed use the User obtains via the Marketplace platform in a particular licensing transaction, as set forth in the Order Confirmation.

"Order Confirmation" is the confirmation CCC provides to the User at the conclusion of each Marketplace transaction. "Order Confirmation Terms" are additional terms set forth on specific Order Confirmations not set forth in the General Terms that can include terms applicable to a particular CCC transactional licensing service and/or any Rightsholder-specific terms.

"Rightsholder(s)" are the holders of copyright rights in the Works for which a User obtains licenses via the Marketplace platform, which are displayed on specific Order Confirmations.

"Terms" means the terms and conditions set forth in these General Terms and any additional Order Confirmation Terms collectively.

"User" or "you" is the person or entity making the use granted under the relevant License. Where the person accepting the Terms on behalf of a User is a freelancer or other third party who the User authorized to accept the General Terms on the User's behalf, such person shall be deemed jointly a User for purposes of such Terms.

"Work(s)" are the copyright protected works described in relevant Order Confirmations.

2) **Description of Service.** CCC's Marketplace enables Users to obtain Licenses to use one or more Works in accordance with all relevant Terms. CCC grants Licenses as an agent on behalf of the copyright rightsholder identified in the relevant Order Confirmation.

3) **Applicability of Terms.** The Terms govern User's use of Works in connection with the relevant License. In the event of any conflict between General Terms and Order Confirmation Terms, the latter shall govern. User acknowledges that Rightsholders have complete discretion whether to grant any permission, and whether to place any limitations on any grant, and that CCC has no right to supersede or to modify any such discretionary act by a Rightsholder.

4) **Representations; Acceptance.** By using the Service, User represents and warrants that User has been duly authorized by the User to accept, and hereby does accept, all Terms.

5) **Scope of License; Limitations and Obligations.** All Works and all rights therein, including copyright rights, remain the sole and exclusive property of the Rightsholder. The License provides only those rights expressly set forth in the terms and conveys no other rights in any Works

6) **General Payment Terms.** User may pay at time of checkout by credit card or choose to be invoiced. If the User chooses to be invoiced, the User shall: (i) remit payments in the manner identified on specific invoices, (ii) unless otherwise specifically stated in an Order Confirmation or separate written agreement, Users shall remit payments upon receipt of the relevant invoice from CCC, either by delivery or notification of availability of the invoice via the Marketplace platform, and (iii) if the User does not pay the invoice within 30 days of receipt, the User may incur a service charge of 1.5% per month or the maximum rate allowed by applicable law, whichever is less. While User may exercise the rights in the License immediately upon receiving the Order Confirmation, the License is automatically revoked and is null and void, as if it had never been issued, if CCC does not receive complete payment on a timely basis.

7) **General Limits on Use.** Unless otherwise provided in the Order Confirmation, any grant of rights to User (i) involves only the rights set forth in the Terms and does not include subsequent or additional uses, (ii) is non-exclusive and non-transferable, and (iii) is subject to any and all limitations and restrictions (such as, but not limited to, limitations on duration of use or circulation) included in the Terms. Upon completion of the licensed use as set forth in the Order Confirmation, User shall either secure a new permission for further use of the Work(s) or immediately cease any new use of the Work(s) and shall render inaccessible (such as by deleting or by removing or severing links or other locators) any further copies of the Work. User may only make alterations to the Work if and as expressly set forth in the Order Confirmation. No Work may be used in any way that is unlawful, including without limitation if such use would violate applicable sanctions laws or regulations, would be defamatory, violate the rights of third parties (including such third parties' rights of copyright, privacy, publicity, or other tangible or intangible property), or is otherwise illegal, sexually explicit, or obscene. In addition, User may not conjoin a Work with any other material that may result in damage to the reputation of the Rightsholder. Any unlawful use will render any licenses hereunder null and void. User agrees to inform CCC if it becomes aware of any infringement of any rights in a Work and to cooperate with any reasonable request of CCC or the Rightsholder in connection therewith.

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13) **Effect of Breach.** Any failure by User to pay any amount when due, or any use by User of a Work beyond the scope of the License set forth in the Order Confirmation and/or the Terms, shall be a material breach of such License. Any breach not cured within 10 days of written notice thereof shall result in immediate termination of such License without further notice. Any unauthorized (but licensable) use of a Work that is terminated immediately upon notice thereof may be liquidated by payment of the Rightsholder's ordinary license price therefor; any unauthorized (and unlicensable) use that is not terminated immediately for any reason (including, for example, because materials containing the Work cannot reasonably be recalled) will be subject to all remedies available at law or in equity, but in no event to a payment of less than three times the Rightsholder's ordinary license price for the most closely analogous licensable use plus Rightsholder's and/or CCC's costs and expenses incurred in collecting such payment.

14) **Additional Terms for Specific Products and Services.** If a User is making one of the uses described in this Section 14, the additional terms and conditions apply:

a) ***Print Uses of Academic Course Content and Materials (photocopies for academic coursepacks or classroom handouts).*** For photocopies for academic coursepacks or classroom handouts the following additional terms apply:

i) The copies and anthologies created under this License may be made and assembled by faculty members individually or at their request by on-campus bookstores or copy centers, or by off-campus copy shops and other similar entities.

ii) No License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied) (ii) permit "publishing ventures" where any particular anthology would be systematically marketed at multiple institutions.

iii) Subject to any Publisher Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the academic pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to no more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular anthology, whether photocopied or electronic, at more than one institution of learning;

E) in the case of a photocopy permission, no materials may be entered into electronic memory by User except in order to produce an identical copy of a Work before or during the academic term (or analogous period) as to which any particular permission is granted. In the event that User shall choose to retain materials that are the subject of a photocopy permission in electronic memory for purposes of producing identical copies more than one day after such retention (but still within the scope of any permission granted), User must notify CCC of such fact in the applicable permission request and such retention shall constitute one copy actually sold for purposes of calculating permission fees due; and

F) any permission granted shall expire at the end of the class. No permission granted shall in any way include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied).

iv) Books and Records; Right to Audit. As to each permission granted under the academic pay-per-use Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any photocopies sold or by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this License for any reason.

b) ***Digital Pay-Per-Uses of Academic Course Content and Materials (e-coursepacks, electronic reserves, learning management systems, academic institution intranets).*** For uses in e-coursepacks, posts in electronic reserves, posts in learning management systems, or posts on academic institution intranets, the following additional terms apply:

i) The pay-per-uses subject to this Section 14(b) include:

A) **Posting e-reserves, course management systems, e-coursepacks for text-based content,** which grants authorizations to import requested material in electronic format, and allows electronic access to this material to members of a designated college or university class, under the direction of an instructor designated by the college or university, accessible only under appropriate electronic controls (e.g., password);

B) **Posting e-reserves, course management systems, e-coursepacks for material consisting of photographs or other still images not embedded in text,** which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorization: to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above, including any necessary resizing, reformatting or modification of the resolution of such requested material (provided that such modification does not alter the underlying editorial content or meaning of the requested material, and provided that the resulting modified content is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the Terms), but not including any other form of manipulation, alteration or editing of the requested material;

C) **Posting e-reserves, course management systems, e-coursepacks or other academic distribution for audiovisual content,** which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorizations: (i) to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above; (ii) to display and perform the requested material to such members of such class in the physical classroom or remotely by means of streaming media or other video formats; and (iii) to "clip" or reformat the requested material for purposes of time or content management or ease of delivery, provided that such “clipping” or reformatting does not alter the underlying editorial content or meaning of the requested material and that the resulting material is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the Terms. Unless expressly set forth in the relevant Order Conformation, the License does not authorize any other form of manipulation, alteration or editing of the requested material.

ii) Unless expressly set forth in the relevant Order Confirmation, no License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied or, in the case of Works subject to Sections 14(b)(1)(B) or (C) above, as described in such Sections) (ii) permit "publishing ventures" where any particular course materials would be systematically marketed at multiple institutions.

iii) Subject to any further limitations determined in the Rightsholder Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the electronic course content pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to not more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular materials, whether photocopied or electronic, at more than one institution of learning;

E) electronic access to material which is the subject of an electronic-use permission must be limited by means of electronic password, student identification or other control permitting access solely to students and instructors in the class;

F) User must ensure (through use of an electronic cover page or other appropriate means) that any person, upon gaining electronic access to the material, which is the subject of a permission, shall see:

- a proper copyright notice, identifying the Rightsholder in whose name CCC has granted permission,
- a statement to the effect that such copy was made pursuant to permission,
- a statement identifying the class to which the material applies and notifying the reader that the material has been made available electronically solely for use in the class, and
- a statement to the effect that the material may not be further distributed to any person outside the class, whether by copying or by transmission and whether electronically or in paper form, and User must also ensure that such cover page or other means will print out in the event that the person accessing the material chooses to print out the material or any part thereof.

G) any permission granted shall expire at the end of the class and, absent some other form of authorization, User is thereupon required to delete the applicable material from any electronic storage or to block electronic access to the applicable material.

iv) Uses of separate portions of a Work, even if they are to be included in the same course material or the same university or college class, require separate permissions under the electronic course content pay-per-use Service. Unless otherwise provided in the Order Confirmation, any grant of rights to User is limited to use completed no later than the end of the academic term (or analogous period) as to which any particular permission is granted.

v) Books and Records; Right to Audit. As to each permission granted under the electronic course content Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any electronic copies used by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this license for any reason.

c) ***Pay-Per-Use Permissions for Certain Reproductions (Academic photocopies for library reserves and interlibrary loan reporting) (Non-academic internal/external business uses and commercial document delivery).*** The License expressly excludes the uses listed in Section (c)(i)-(v) below (which must be subject to separate license from the applicable Rightsholder) for: academic photocopies for library reserves and interlibrary loan reporting; and non-academic internal/external business uses and commercial document delivery.

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ii) the input of Works or reproductions thereof into any computerized database;

iii) reproduction of an entire Work (cover-to-cover copying) except where the Work is a single article;

iv) reproduction for resale to anyone other than a specific customer of User;

v) republication in any different form. Please obtain authorizations for these uses through other CCC services or directly from the rightsholder.

Any license granted is further limited as set forth in any restrictions included in the Order Confirmation and/or in these Terms.

d) ***Electronic Reproductions in Online Environments (Non-Academic-email, intranet, internet and extranet).*** For "electronic reproductions", which generally includes e-mail use (including instant messaging or other electronic transmission to a defined group of recipients) or posting on an intranet, extranet or Intranet site (including any display or performance incidental thereto), the following additional terms apply:

i) Unless otherwise set forth in the Order Confirmation, the License is limited to use completed within 30 days for any use on the Internet, 60 days for any use on an intranet or extranet and one year for any other use, all as measured from the "republication date" as identified in the Order Confirmation, if any, and otherwise from the date of the Order Confirmation.

ii) User may not make or permit any alterations to the Work, unless expressly set forth in the Order Confirmation (after request by User and approval by Rightsholder); provided, however, that a Work consisting of photographs or other still images not embedded in text may, if necessary, be resized, reformatted or have its resolution modified without additional express permission, and a Work consisting of audiovisual content may, if necessary, be "clipped" or reformatted for purposes of time or content management or ease of delivery (provided that any such resizing, reformatting, resolution modification or “clipping” does not alter the underlying editorial content or meaning of the Work used, and that the resulting material is used solely within the scope of, and in a manner consistent with, the particular License described in the Order Confirmation and the Terms.

15) **Miscellaneous.**

a) User acknowledges that CCC may, from time to time, make changes or additions to the Service or to the Terms, and that Rightsholder may make changes or additions to the Rightsholder Terms. Such updated Terms will replace the prior terms and conditions in the order workflow and shall be effective as to any subsequent Licenses but shall not apply to Licenses already granted and paid for under a prior set of terms.

b) Use of User-related information collected through the Service is governed by CCC's privacy policy, available online at www.copyright.com/about/privacy-policy/.

c) The License is personal to User. Therefore, User may not assign or transfer to any other person (whether a natural person or an organization of any kind) the License or any rights granted thereunder; provided, however, that, where applicable, User may assign such License in its entirety on written notice to CCC in the event of a transfer of all or substantially all of User's rights in any new material which includes the Work(s) licensed under this Service.

d) No amendment or waiver of any Terms is binding unless set forth in writing and signed by the appropriate parties, including, where applicable, the Rightsholder. The Rightsholder and CCC hereby object to any terms contained in any writing prepared by or on behalf of the User or its principals, employees, agents or affiliates and purporting to govern or otherwise relate to the License described in the Order Confirmation, which terms are in any way inconsistent with any Terms set forth in the Order Confirmation, and/or in CCC's standard operating procedures, whether such writing is prepared prior to, simultaneously with or subsequent to the Order Confirmation, and whether such writing appears on a copy of the Order Confirmation or in a separate instrument.

e) The License described in the Order Confirmation shall be governed by and construed under the law of the State of New York, USA, without regard to the principles thereof of conflicts of law. Any case, controversy, suit, action, or proceeding arising out of, in connection with, or related to such License shall be brought, at CCC's sole discretion, in any federal or state court located in the County of New York, State of New York, USA, or in any federal or state court whose geographical jurisdiction covers the location of the Rightsholder set forth in the Order Confirmation. The parties expressly submit to the personal jurisdiction and venue of each such federal or state court.

Last updated October 2022

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Order Date	24-Mar-2023	**Type of Use**	Republish in a thesis/dissertation
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ISSN	1433-3015	**Publisher**	SPRINGER-VERLAG LONDON
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LICENSED CONTENT

Publication Title	The international journal of advanced manufacturing technology	**Rightsholder**	Springer Nature BV
		Publication Type	e-Journal
		Start Page	1
Article Title	Additive manufacturing of recycled plastics: a ‘techno-eco-efficiency’ assessment	**End Page**	26
		URL	http://link.springer-ny.com/link/service/journals/00170/index.htm
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NEW WORK DETAILS

Title	Eco-efficiency Performance Comparison of Additive and Subtractive Manufactured Parts	**Institution Name**	Curtin University, Australia
		Expected Presentation Date	2023-03-31
Instructor Name	Wahidul K. Biswas		

ADDITIONAL DETAILS

The Requesting Person/Organization to Appear on the License	Heshan Jayawardane

REQUESTED CONTENT DETAILS

Title, Description or Numeric Reference of the Portion(s)	Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment	**Title of the Article/Chapter the Portion Is From**	Additive manufacturing of recycled plastics: a 'techno-eco-efficiency' assessment
Editor of Portion(s)	Jayawardane, Heshan; Davies, Ian J.; Gamage, J. R.; John, Michele; Biswas, Wahidul K.	**Author of Portion(s)**	Jayawardane, Heshan; Davies, Ian J.; Gamage, J. R.; John, Michele; Biswas, Wahidul K.
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14) **Additional Terms for Specific Products and Services.** If a User is making one of the uses described in this Section 14, the additional terms and conditions apply:

a) ***Print Uses of Academic Course Content and Materials (photocopies for academic coursepacks or classroom handouts).*** For photocopies for academic coursepacks or classroom handouts the following additional terms apply:

i) The copies and anthologies created under this License may be made and assembled by faculty members individually or at their request by on-campus bookstores or copy centers, or by off-campus copy shops and other similar entities.

ii) No License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied) (ii) permit "publishing ventures" where any particular anthology would be systematically marketed at multiple institutions.

iii) Subject to any Publisher Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the academic pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to no more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular anthology, whether photocopied or electronic, at more than one institution of learning;

E) in the case of a photocopy permission, no materials may be entered into electronic memory by User except in order to produce an identical copy of a Work before or during the academic term (or analogous period) as to which any particular permission is granted. In the event that User shall choose to retain materials that are the subject of a photocopy permission in electronic memory for purposes of producing identical copies more than one day after such retention (but still within the scope of any permission granted), User must notify CCC of such fact in the applicable permission request and such retention shall constitute one copy actually sold for purposes of calculating permission fees due; and

F) any permission granted shall expire at the end of the class. No permission granted shall in any way include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied).

iv) Books and Records; Right to Audit. As to each permission granted under the academic pay-per-use Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any photocopies sold or by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this License for any reason.

b) ***Digital Pay-Per-Uses of Academic Course Content and Materials (e-coursepacks, electronic reserves, learning management systems, academic institution intranets).*** For uses in e-coursepacks, posts in electronic reserves, posts in learning management systems, or posts on academic institution intranets, the following additional terms apply:

i) The pay-per-uses subject to this Section 14(b) include:

A) **Posting e-reserves, course management systems, e-coursepacks for text-based content,** which grants authorizations to import requested material in electronic format, and allows electronic access to this material to members of a designated college or university class, under the direction of an instructor designated by the college or university, accessible only under appropriate electronic controls (e.g., password);

B) **Posting e-reserves, course management systems, e-coursepacks for material consisting of photographs or other still images not embedded in text,** which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorization: to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above, including any necessary resizing, reformatting or modification of the resolution of such requested material (provided that such modification does not alter the underlying editorial content or meaning of the requested material, and provided that the resulting modified content is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the Terms), but not including any other form of manipulation, alteration or editing of the requested material;

C) **Posting e-reserves, course management systems, e-coursepacks or other academic distribution for audiovisual content,** which grants not only the authorizations described in Section 14(b)(i)(A) above, but also the following authorizations: (i) to include the requested material in course materials for use consistent with Section 14(b)(i)(A) above; (ii) to display and perform the requested material to such members of such class in the physical classroom or remotely by means of streaming media or other video formats; and (iii) to "clip" or reformat the requested material for purposes of time or content management or ease of delivery, provided that such “clipping” or reformatting does not alter the underlying editorial content or meaning of the requested material and that the resulting material is used solely within the scope of, and in a manner consistent with, the particular authorization described in the Order Confirmation and the Terms. Unless expressly set forth in the relevant Order Conformation, the License does not authorize any other form of manipulation, alteration or editing of the requested material.

ii) Unless expressly set forth in the relevant Order Confirmation, no License granted shall in any way: (i) include any right by User to create a substantively non-identical copy of the Work or to edit or in any other way modify the Work (except by means of deleting material immediately preceding or following the entire portion of the Work copied or, in the case of Works subject to Sections 14(b)(1)(B) or (C) above, as described in such Sections) (ii) permit "publishing ventures" where any particular course materials would be systematically marketed at multiple institutions.

iii) Subject to any further limitations determined in the Rightsholder Terms (and notwithstanding any apparent contradiction in the Order Confirmation arising from data provided by User), any use authorized under the electronic course content pay-per-use service is limited as follows:

A) any License granted shall apply to only one class (bearing a unique identifier as assigned by the institution, and thereby including all sections or other subparts of the class) at one institution;

B) use is limited to not more than 25% of the text of a book or of the items in a published collection of essays, poems or articles;

C) use is limited to not more than the greater of (a) 25% of the text of an issue of a journal or other periodical or (b) two articles from such an issue;

D) no User may sell or distribute any particular materials, whether photocopied or electronic, at more than one institution of learning;

E) electronic access to material which is the subject of an electronic-use permission must be limited by means of electronic password, student identification or other control permitting access solely to students and instructors in the class;

F) User must ensure (through use of an electronic cover page or other appropriate means) that any person, upon gaining electronic access to the material, which is the subject of a permission, shall see:

- a proper copyright notice, identifying the Rightsholder in whose name CCC has granted permission,
- a statement to the effect that such copy was made pursuant to permission,

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G) any permission granted shall expire at the end of the class and, absent some other form of authorization, User is thereupon required to delete the applicable material from any electronic storage or to block electronic access to the applicable material.

iv) Uses of separate portions of a Work, even if they are to be included in the same course material or the same university or college class, require separate permissions under the electronic course content pay-per-use Service. Unless otherwise provided in the Order Confirmation, any grant of rights to User is limited to use completed no later than the end of the academic term (or analogous period) as to which any particular permission is granted.

v) Books and Records; Right to Audit. As to each permission granted under the electronic course content Service, User shall maintain for at least four full calendar years books and records sufficient for CCC to determine the numbers of copies made by User under such permission. CCC and any representatives it may designate shall have the right to audit such books and records at any time during User's ordinary business hours, upon two days' prior notice. If any such audit shall determine that User shall have underpaid for, or underreported, any electronic copies used by three percent (3%) or more, then User shall bear all the costs of any such audit; otherwise, CCC shall bear the costs of any such audit. Any amount determined by such audit to have been underpaid by User shall immediately be paid to CCC by User, together with interest thereon at the rate of 10% per annum from the date such amount was originally due. The provisions of this paragraph shall survive the termination of this license for any reason.

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15) **Miscellaneous.**

a) User acknowledges that CCC may, from time to time, make changes or additions to the Service or to the Terms, and that Rightsholder may make changes or additions to the Rightsholder Terms. Such updated Terms will replace the prior terms and conditions in the order workflow and shall be effective as to any subsequent Licenses but shall not apply to Licenses already granted and paid for under a prior set of terms.

b) Use of User-related information collected through the Service is governed by CCC's privacy policy, available online at www.copyright.com/about/privacy-policy/.

c) The License is personal to User. Therefore, User may not assign or transfer to any other person (whether a natural person or an organization of any kind) the License or any rights granted thereunder; provided, however, that, where applicable, User may assign such License in its entirety on written notice to CCC in the event of a transfer of all or substantially all of User's rights in any new material which includes the Work(s) licensed under this Service.

d) No amendment or waiver of any Terms is binding unless set forth in writing and signed by the appropriate parties, including, where applicable, the Rightsholder. The Rightsholder and CCC hereby object to any terms contained in any writing prepared by or on behalf of the User or its principals, employees, agents or affiliates and purporting to govern or otherwise relate to the License described in the Order Confirmation, which terms are in any way inconsistent with any Terms set forth in the Order Confirmation, and/or in CCC's standard operating procedures, whether such writing is prepared prior to, simultaneously with or subsequent to the Order Confirmation, and whether such writing appears on a copy of the Order Confirmation or in a separate instrument.

e) The License described in the Order Confirmation shall be governed by and construed under the law of the State of New York, USA, without regard to the principles thereof of conflicts of law. Any case, controversy, suit, action, or proceeding arising out of, in connection with, or related to such License shall be brought, at CCC's sole discretion, in any federal or state court located in the County of New York, State of New York, USA, or in any federal or state court whose geographical jurisdiction covers the location of the Rightsholder set forth in the Order Confirmation. The parties expressly submit to the personal jurisdiction and venue of each such federal or state court.

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