Patricia Nyamekye

LIFE CYCLE COST-DRIVEN DESIGN FOR ADDITIVE MANUFACTURING: THE FRONTIER TO SUSTAINABLE MANUFACTURING IN LASER-BASED POWDER BED FUSION

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Abstract

Patricia Nyamekye
Life cycle cost-driven design for additive manufacturing: the frontier to sustainable manufacturing in laser-based powder bed fusion
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Additive manufacturing (AM) is a manufacturing method that creates components in a layer-wise manner. Laser-based powder bed fusion (L-PBF) is one of the most used AM subcategories to manufacture metal components, referred to in this thesis as metal AM/L-PBF. The effective use of AM offers a trifactor of part complexity, simplified manufacturing and improved performance with digital tools to the achievement of resource-efficient, cost-effective, durable components as well as waste and emissions reductions. Currently, this manufacturing method can be used to manufacture optimised, lightweight and multi-material components. AM has inherent limitations that need conscious designing and planning to be able to offer the expected benefits. The design system (designing and manufacturing) can either positively or negatively influence the integrity of the final component. Critical consideration of these is often required to avoid unwanted defects that may influence the performance of the final components. This often increases labour intensiveness, digital tools, time and consequent increase in costs. The practice of sustainable manufacturing focuses on product design that has the least negative environmental impact through economically-sound processes that support waste reduction and long-term cycle usage goals, termed *circular economy,* (CE). The question then is how can metal AM/L-PBF enhance sustainability and the CE to meet the goals of sustainable manufacturing? How can the benefits offered by metal AM/L-PBF be evaluated from a life cycle (LC) perspective?

The principal motivation of this thesis was to offer a critical fact-based contribution that is free from subjective or commercial considerations to support the sustainability arguments of metal AM/L-PBF. The main aim of the thesis was to identify the hotspots of metal AM/L-PBF that could be optimised to improve sustainable practice. The objective of this thesis was to theoretically and experimentally study how metal L-PBF enhances the achievement of sustainability and the CE through energy-efficient, material-efficient processing and the minimisation of waste and emissions.

Firstly, this thesis includes investigatory studies on the environmental and economic aspects of sustainability of metal AM/L-PBF through life cycle inventory (LCI) and supply chain analyses. A preliminary review of the social aspect of sustainability is generally presented. Secondly, the thesis incorporates a practical investigation of the effect of process parameters in metal L-PBF on melt pool formation and spatial resolution of finely-featured metal components. Thirdly, the thesis uses reviews and case studies to assess the influence of simulation-driven design for additive manufacturing (simulation-driven DfAM) on the life cycle cost (LCC). Fourthly, the thesis investigates the flexibility and suitability of manufacturing intricate and multi-material electrochemical separation units using reviewed data. The review focused on how metal L-PBF manufactured electrodes improved performance and cost-efficiency. The final part of the thesis was carried out as discussions with industrial representatives on the benefits/limitations of metal L-PBF to identify practical strategic approaches to harness the identified benefits/limitations of metal AM/L-PBF. The discussion aimed to modify an initially created LCC-driven model in publication 4 and to highlight its suitability as a useful tool to support decision-making in industries to the adoption of metal AM/L-PBF. Business process modelling, (value chain analysis (VCA); strength, weakness, opportunities and threat (SWOT) models) were used to identify the best adoption plan to maximise value creation from idea generation to end-of-life (EOL).

The results of this thesis showed that metal L-PBF lessens the need and distance of transportation thereby reduces transport-related emissions. Metal L-PBF reduces the need for spare parts and inventory with on-demand manufacturing which reduces cost and waste. Again, this thesis showed that L-PBF allows optimised designs with intricate internal and outer geometries to be manufactured in resource-efficient and cost-efficient manner. The results of the experimental study on the process parameters showed that optimising process parameter values directly enhances part qualify and reduces defects. The potential to control the process efficiency is one way by which raw material and high energy utilisations can be improved in metal L-PBF. The results of the LCC studies identified key drivers to cost and how they could be optimised in metal L-PBF using digital simulations and DfAM rules, referred to in this thesis as LCC-driven DfAM. The simulation-driven DfAM study showed how digital tools allow for the acceleration of sustainable products via product optimisation while maintaining cost-effectiveness and waste reductions. The results of the review on metal L-PBF manufactured separation units for electrochemical application showed that the method made it possible to create intricate structures such as lattices and conformal flow channels. This benefit offered the possibility of improved functional multi-metal separation units.

The main outcome of this thesis is the first-ever integrated LCC-driven DfAM model that can be used as a decision-making tool to the adoption of metal AM/L-PBF towards high performing, resource efficiency, cost-efficient components. The model can be used in industries to identify best practices that can help create optimised metal components without adding to costs. The model highlights the phases in which the greatest cost reductions are achievable from the design, manufacturing, use and EOL phases. The thesis shows that metal AM/L-PBF is constantly developing. These include innovations and new solutions to improve productivity, resource efficiency as well as the reduction of waste and emissions. Metal AM/L-PBF can enhance resource consumption, reduce costs, drive innovations in sustainable business practice and offer means of competitiveness. The main conclusion of this thesis is that metal L-PBF offers means to optimised product design, possibilities of reducing raw material usage, operational costs, waste and emissions.

Plans to experimentally compare the performance of L-PBF and CNC-machining manufactured components and the effect of build platform utilisation on specific energy consumption (SEC) in L-PBF did not materialise due to a lack of funds. The thesis identified that ongoing sustainability studies of metal AM/L-PBF do not include the entire aspects of sustainability and value chain. For example, the social aspects, experimental energy and raw material consumptions during the powder production phases. Further studies could include the limitations of this thesis and provide comprehensive continuity of the subject to overcome some of the identified gaps in literature and process limitations.

Keywords: Additive manufacturing, design for additive manufacturing, (DfAM), circular economy, (CE), laser-based powder bed fusion, (L-PBF), life cycle cost, LCC-driven, metal AM, metal L-PBF, simulation-driven DfAM, sustainability.

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I would like to express my utmost gratitude to my first supervisor, Professor Heidi Piili, for her patience and counsel throughout this academic journey. Her kind and thoughtful words got me going most of the time. Her tranquillity and knowledge were inspiring and motivating. The shared humour helped me manage difficult times during the last year of this journey. Am grateful for the opportunity to work at the Laboratory of Laser Materials Processing and Additive Manufacturing (Laser&AM).

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Finally, my appreciation goes to the ‘Recovery of gold from the secondary resources by novel electrochemical reactors realised with additive manufacturing (ReGold-AM)’ project for the support I received for Publication 5 of this study. ReGold-AM is funded by the Academy of Finland, decision number 325003 from 01.09.2019 to 31.08.2023. The project aims to construct novel electrochemical reactors for gold recovery. The project has been carried out in co-operation with the research group of Hydrometallurgy for Urban Mining.

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Patricia Nyamekye
May 2021
Lappeenranta, Finland.

To Dedication

This thesis is dedicated to my son, Brian Nana Adu Appiah, my mentor and role model, Professor Heidi Piili, cousin-sibling and to the memory of my grandmother, Madam Akosua Addae (dod:05.02.2021).

'Discovery is seeing what everybody else has seen and thinking what nobody else has thought'. Albert Szent-Gyorgyi.

Make the world a better place! The little efforts towards resource efficiency can help create a better now and a future sustainable world.

A childhood dream has become a reality on this day May 5th, 2021.

Contents

List of publications

This dissertation contains material from the following papers. The rights have been granted by the publishers to include the material in the dissertation.

I. Nyamekye, P., Leino, M., Piili, H., & Salminen, A. (2015). 'Overview of Sustainability Studies of CNC Machining and LAM of Stainless Steel'. *Physics Procedia*. Elsevier B.V., 78, pp. 367–376.

II. Nyamekye, P., Piili, H., Leino, M., & Salminen, A. (2017). 'Preliminary Investigation on Life Cycle Inventory of Powder Bed Fusion of Stainless Steel'. *Physics Procedia*. Elsevier B.V., 89, pp. 108–121.

III. Laitinen, V., Piili, H., Nyamekye, P., Ullakko, K., & Salminen, A. (2019). 'Effect of process parameters on the formation of single track in pulsed laser powder bed fusion', in *Procedia Manufacturing*. Elsevier B.V., 36, pp. 176-183.

IV. Nyamekye, P., Unt, A., Salminen, A., & Piili, H. (2020). 'Integration of simulation-driven DFAM and LCC analysis for decision making in L-PBF', *Metals*. 10(9), pp. 1–20.

V. Nyamekye, P., Nieminen, P., Bilesan, M. R., Repo, E., Piili, H., & Salminen, A. (2021). 'Prospects for laser-based powder bed fusion in the manufacturing of metal electrodes: A review', *Applied Materials Today*. Elsevier Ltd., 23(101040).

Author's contribution

The author was the principal contributor responsible for the theoretical reviews in publications I, II, IV and V and the experimental investigation in publications I and II. The author was the principal contributor responsible for writing the final manuscript for publications I, II, IV and V.

I. Nyamekye, P., Leino, M., Piili, H., & Salminen, A. (2015). 'Overview of Sustainability Studies of CNC Machining and LAM of Stainless Steel'. *Physics Procedia*. Elsevier B.V., 78, pp. 367–376.

The reviews and model developed in this paper were carried out by the author. The paper was discussed, commented on, and modified together by the candidate, MSc Maija Leino and Prof. Heidi Piili. Advice and recommendations were received from Prof. Antti Salminen. MSc Ville-Pekka Matilainen and DSc Ilkka Poutiainen performed the experiments in this study. I am the first author and correspondence of this article.

II. Nyamekye, P., Piili, H., Leino, M., & Salminen, A. (2017). ‘Preliminary Investigation on Life Cycle Inventory of Powder Bed Fusion of Stainless Steel’. *Physics Procedia*. Elsevier B.V., 89, pp. 108–121.

The author conducted the analysis of experimental data and wrote the reviews in this paper. The paper was discussed, commented on, and modified together by the candidate, MSc Maija Leino and Prof. Heidi Piili. Advice and recommendations were received from Prof. Antti Salminen. MSc Ville-Pekka Matilainen and DSc Ilkka Poutiainen executed the experimental part of this study. I am the first author and correspondence of this article.

III. Laitinen, V., Piili, H., Nyamekye, P., Ullakko, K., & Salminen, A. (2019). ’Effect of process parameters on the formation of single track in pulsed laser powder bed fusion’, in *Procedia Manufacturing*. Elsevier B.V., 36, pp. 176-183.

The author investigated and wrote about the effects of process parameters, (scanning strategy) in laser additive manufacturing. The paper was discussed, commented on, and modified by the candidate and other authors. MSc Ville Laitinen is the first author and correspondence of this article.

IV. Nyamekye, P., Unt, A., Salminen, A., & Piili, H. (2020). ‘Integration of simulation-driven DFAM and LCC analysis for decision making in L-PBF’, *Metals*. 10(9), pp. 1–20.

The conceptualisation, methodology, validation, investigation, data curation, original draft preparation, review and editing, visualisation of the publication was performed by the author. The paper was discussed, commented on, and modified by the candidate, DSc Anna Unt, Prof. Antti Salminen and Prof. Heidi Piili. The author received advice and recommendations from DSc Anna Unt, Prof. Antti Salminen and Prof. Heidi Piili. I am the first author and correspondence of this article.

V. Nyamekye, P., Nieminen, P., Bilesan, M. R., Repo, E., Piili, H., & Salminen, A. (2021). ‘Prospects for laser-based powder bed fusion in the manufacturing of metal electrodes: A review’, *Applied Materials Today*. Elsevier Ltd., 23(101040).

The author contributed to data acquisition, methodology, investigation, validation, visualisation, writing, reviewing and editing. All authors contributed to reviewing, modifying and editing. The paper was discussed, commented on, and modified by the candidate, Pinja Nieminen, MSc Mohammed Reza Bilesan, Prof. Eveliina Repo, Prof. Antti Salminen and Prof. Heidi Piili. I am the first author and correspondence of this article.

Nomenclature

Symbol	Unit	Explanation
Au	-	Gold
Bi	-	Bismuth
CH_4	-	Methane
CO_2	-	Carbon dioxide
Cu	-	Copper
H_2O	-	Water vapour
E^3	-	Sustainability
P	W	Laser power
V	mm/s	Scanning speed
m	kg	Mass
N_2O	-	Nitrous oxide
Wt.	-	Weight
SEC	kWh/kg	Specific energy consumption
Sn	-	Tin
t	µm	Layer thickness
t_p	s	Pulse length
VED	J/mm^3	Volumetric energy density
Δys	µm	Hatch distance

Units	Explanation
%	Percentage
µm	Micrometre
µs	Microsecond
°C	Degrees Celsius
a.u.	Arbitrary units, values without a specific unit
cm	Centimetre
h	Hour
K/s	Kelvin per second
kW	Kilowatt
kWh	Kilowatt hour
kWh/kg	Kilowatt hour/kilogram
m	Meter
mm	Millimetre
mm/s	Millimetre per second
MJ/kg	Megajoule per kilogram
MPa	Megapascal
W	Watt

Superscripts

Subscripts

Abbreviations	**Explanation**
2D	Two-dimensional
3D	Three dimensional
3Rs	Reduce, reuse, recycle
AM	Additive manufacturing
AI	Artificial intelligence
AR	Augmented reality
ASTM	American Society for Testing and Materials
BJ	Binder jetting
CAD	Computer-aided design
CE	Circular economy
CF	Carbon footprint
CFCs	Chlorofluorocarbons
CFD	Computational fluid dynamics
CNC	Computer numerical control
CM	Conventional manufacturing
CR	Corporate responsibility
CSR	Corporate social responsibility
CW	Continuous wave
DfAM	Design for additive manufacturing
DED	Directed energy deposition
DMLS	Direct metal laser sintering
EB	Electron beam
ECM	Electrochemical machining
EDM	Electrical discharge machining
ECUs	Energy-consuming units
EOL	End-of-life
EOS	Electrical Optical Systems
EBM™	Electron beam melting
EPA	Environmental Protection Agency
FEA	Finite element analysis
FEM	Finite element method
ISO	International standard organisation
IoT	Internet of Things
LAM	Laser additive manufacturing
LC	Life cycle
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
L-PBF	Laser-based powder bed fusion

SL	Sheet lamination
ME	Material extrusion
MJ	Material jetting
NASA	National Aeronautics and Space Administration
O1	Objective 1
O2	Objective 2
O3	Objective 3
OEMs	Original equipment manufacturers
P	Pulsed wave
P1	Publication 1
P2	Publication 2
P3	Publication 3
P4	Publication 4
P5	Publication 5
PBF	Powder bed fusion
RI	Research question 1
R2	Research question 2
R3	Research question 3
REBs	Rechargeable batteries
SDGs	Sustainable development goals
SLM	Selective laser melting
SME	Small and medium enterprise
STL	Standard Tessellation Language
SWOT	Strength, weakness, opportunities and threat
UN	United Nations
US	United States
UTS	Ultimate tensile strength
Vat	Vat photopolymerisation
VCA	Value chain analysis

1 Introduction

Industrial engineering comprises interrelated core activities, such as research, development, designing, fabrication, qualification and other support activities that help create successful components capable of satisfying the needs of customers. Manufacturing methods require raw material and energy as input to produce outputs to satisfy human needs. Manufacturing methods (for example, conventional machining and additive manufacturing) consume differently energy and raw material (Z. Y. Liu et al., 2018). Comparable manufacturing methods can both produce the same products, however, one can offer better resource efficiency, cost efficiency, waste and emission reductions than the other. Different manufacturing methods apply certain approaches for reducing energy consumption, raw material usage and waste creation. The design process and manufacturing methods used to create these components constitute a core aspect of the component. Detailed component design and the manufacturing process can either positively or negatively influence the reliability and properties of the final component. The product design in the conventional design flow is often predetermined based on the capabilities of the available tools and machinery (Tan et al., 2020). Critical consideration of these is often required to avoid unwanted defects that may negatively influence the performance of the final components. This often increases labour intensiveness, resource consumption, waste creation and time consumption, thereby increasing costs. A substantial amount of time is used on identifying ways of satisfying the predefined constraints of individual manufacturing methods during the design phase. This often restricts the creativity of the designer as the freedom to design is restricted by, for example, tools and mould-set limits. Consequently, a good engineer is required to spend significant efforts and time on determining the manufacturability of the intended designs.

Sustainability and the circular economy (CE) have become an integral part of almost all industrial sectors. The current industrial era requires industries to be environmentally, economically and socially sustainable (Büyüközkan & Karabulut, 2018). Meeting sustainability goals and the CE targets requires a change of approach to the design system (designing and manufacturing). The manufacturing sector is making a conscious effort to develop social-ecological and cost-effective products and processes to meet the needs of customers and regulatory policies. Emerging technologies, such as additive manufacturing (AM), machine learning, automation, Internet of Things (IoT) and simulations offer new ways to find solutions that can enhance productivity and cater for resource and economic inefficiencies (Ilie et al., 2019; Lasi et al., 2014). The creation and development of such innovative methods and tools are leveraging the efforts of industries of improving efficiency with low energy-consuming processing methods, reduced raw material needs, increased product lifetime, minimisation of waste and emissions.

AM also known as three-dimensional printing (3D printing), is defined as the *process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies* (ISO/ASTM 52900:2015). In the last three decades, AM, has evolved from being a prototype fabrication method to a method capable of manufacturing functional components (DE

Editors, 2010; Jiménez et al., 2021; Lind et al., 2003). AM continues to emerge as a novel manufacturing technology that allows unique designs (see Appendix A), shorten the product development phase, reduced costs, waste and emissions in different industrial sectors (see Appendix B). A component in this thesis refers to the basic elements of a product that embodies a core design concept. Components and parts are used interchangeably in this thesis to mean the same thing. AM enables the minisation of costs and negative environmental impacts while conserving energy and natural resources with low consumptions. AM allows new components designs that are impossible with conventional manufacturing methods to improve process efficiencies and cost-effectiveness through optimised designs, simplified manufacturing and improved performance. AM offers manufacturing companies the option to swift product design of lightweight, reliable, durable and cost-effective components capable of satisfying sustainable goals and the CE targets. Reducing the weight of metal components in high-end applications such as automotive and aerospace can reduce fuel consumption, creation of waste and emissions thereby reduce the carbon footprint (CF) during their LC (H. Lee et al., 2017). Albeck-Ripka (2019) defines a carbon footprint as *the total amount of greenhouse gas emissions that come from the production, use and end-of-life of a product or service.*

Laser-based powder bed fusion (L-PBF) is a powder bed fusion (PBF), a sub-category of AM, that is capable of manufacturing high-end metal components. Metal L-PBF is a layer-by-layer manufacturing method that uses digital data to create three dimensional physical components from using metal powder with the assistance of laserbased energy. Laser beam is used to melt regions of powder bed in an enclosed chamber.

1.1 Background

One global problem that has continually created concern for the industrial sector is the creation of waste and high levels of emissions introduced to the atmosphere that contribute to global warming. Global warming is the long-term heating up of the earth's climate system as a result of trapped heat radiation escaping the earth to the space sphere (Jancis Robinson, 2020; NASA, 2020a). Gases released in the form of emissions form layers in the atmosphere that cause an increase in global temperature of approximately 30°C compared to normal levels (Jancis Robinson, 2020). This phenomenon is referred to as the *greenhouse effect* and is caused by greenhouse gases (GHGs), including water vapour (H_2O), carbon dioxide (CO_2), methane, (CH_4), dinitrogen oxide (N_2O) and chlorofluorocarbons (CFCs) (NASA, 2020b). CO_2 is a long-lasting component of GHGs (Jancis Robinson, 2020; NASA, 2020b) and often contributes most (about 65%) to GHG emissions (US EPA, 2014). CO_2 is caused by both human-induced and naturally occurring activities such as respiration, deforestation and industrial activities including the burning of fossil fuels and raw material production (CHE, 2017; NASA, 2020b) (see Appendix C). The use of natural resources to make raw material continues to increase as the population and the needs of mankind continue to grow. This causes the depletion of natural resources, creates waste and emissions to the ecosystem. Conscious efforts and education are needed to curtail such problems. There must be measures such as the reduction and replacement of raw material to ensure the safeguard of the biosphere. There is also the need to reduce the amount of waste created and released emissions into the ecosystem to protect biodiversity.

The need to control the resources consumption , creation of waste and harmful emissions that negatively impact the ecosystem service including the functioning of biodiversity and human wellbeing are few of the driving forces to sustainable manufacturing (Millennium Ecosystem Assessment, 2005). Concerns to mitigate climate change is also one of the driving forces to finding sustainable design and products (The Royal Academy of Engineering, 2012). US EPA (2020) defines sustainable manufacturing as *the creation of manufactured products through economically sound processes that minimise negative environmental impacts while conserving energy and natural resources.* Life cycle thinking is the wide-ranging tools and actions that supports engineers and practitioners to design sustainable product/process alternatives relating to life cycle approach (Mazzi, 2019). These include life cycle assessment (LCA), life cycle cost (LCC) and social life cycle assessment (S-LCA) (Ren & Toniolo, 2019). LCA is defined as the *compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle* (ISO, 2006). LCA is the methodology to obtain quantifiable and objective information for sustainable production alternatives. *LCC* can be described *as the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion and/or decommission* (SAE, 1999). LCC can also be described *as cradle to grave costs summarized as an economic model of evaluating alternatives for equipment and projects* (Barringer, 2003). LCC is a tool that can be used to estimate the life-long costs of components to make the selection of alternative products/processes based on the impact of both pending and future costs. S-LCA is defined as *a technique for collecting, analysing and communicating information about the social conditions and impacts associated with production and (in some applications) consumption (Norris et al., 2014).* S-LCA is a tool that can be used to evaluate the social aspects of sustainability of both the positive and negative impacts of products/processes along the LC.

Identifying ways to improve energy efficiency, raw material efficiency and waste reduction are some of the approaches to achieving the existing goal of reducing around 80–95% of GHG emissions at 1990 levels by 2050 (Lawrence et al. 2019). Material efficiency measures the quantity of useful output and generated waste per unit of input material. The efficient use of raw material could significantly reduce wastes and emissions. Strategies that support lightweightness, energy-efficient products, fuel switching, renewable energy, material recycling and emission reduction could mitigate climate change in the industrial sector (C2ES, 2019; Fischedick et., 2014; IEA, 2017; Lawrence et al., 2019).

Newly emerging industrial technologies that enhance design optimisation, energy, material and other efficiencies with extended component lifetime must be recognised to promote their continuous development (Fischedick et., 2014; Hertwich et al., 2019; IEA, 2020; UNEP, 2020) in promoting the CE. Products design optimisation is an effective approach to achieve light-weighting and downsizing of components in the design phase. Optimised designs could reduce the volume of materials used as input or removed as waste to be recycled during production for improved material yield. Several studies have classified AM as one of the key drivers along the value chain for creating intelligent and efficient products (Godina et al., 2020; Jimo et al., 2019; Lee et al., 2017; Tofail et al., 2018). Digital design and simulations tools can be used to create and identify unique designs for AM and in consideration of the capabilities of AM. (see Appendix C).

AM allows part consolidation and light-weighting, which reduces the volume of raw material and the number of manufacturing methods needed to make parts (Campbell & Bourell, 2020; Daraban et al., 2019; Najmon et al., 2019; SHINING 3D, 2020). AM can result in around a 65–99% material utilisation rate and minimised waste and emissions (Najmon et al., 2019; Serres et al., 2011). Energy consumption during the manufacturing phase with AM remains a concern. An enormous amount of energy is consumed during the actual building of components (Z. Y. Liu et al., 2018; Sharif Ullah et al., 2015). Monitoring and measuring input/output energy using mass flow analysis helps to identify the hotspots that could be targeted to control such undesirable consumptions. According to Sculpteo (2020), the increase in sustainable technologies and the development of new materials for AM systems could drive its growth by 47%. The advancement of sustainability measuring tools has supported the strategies impacting sustainable practices in existing and emerging technologies.

A life cycle inventory (LCI) tool developed by Kellens et al. (2012) is an example of a tool that is used to measure the environmental aspect of sustainability of AM. ISO 14040:2006 defines LCI as a *phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle* (ISO, 2006). LCI entails *an inventorying of input/output data concerning the system being studied* (ISO, 2006). ISO 14001:2015 (2015) defines environmental aspects as *an element of an organization's activities or products or services that interacts or can interact with the environment* (ISO, 2015). An LCI study excludes potential burden shifting as it considers the different phases of a life cycle (LC) on an equal scale. This prevents the tendency to increase or decrease the impact of the respective LC phase. The efficiencies in terms of energy usage, raw material consumption, created waste and emissions can be evaluated with such a methodological tool. The systematic LCI tool developed by Kellens et al. (2012) was used in the LCI study in **Publication 2**.

1.2 Motivation and aims of the thesis

The continuous increase in the depletion of natural resources and the volume of negative releases as a result of industrial sectors remain a concern. Releases are defined as *emissions to air and discharges to water and soil* (ISO, 2006). Measures to guide the product design and selection of sustainable methods that can create resource-efficient products and services continue to develop. The design of components can be optimised to intensify raw material and energy efficiencies, monetary efficacy and emission reduction. However, there is a question as to whether these improvements are the best options for controlling the negative and unpredictable scarcity of resources. There are several aspects to this question from sustainability (social, environmental, economic), circularity and technical perspectives. This question must entail the entire LC to reduce the possibility of worst performance. However, the environmental and economic aspects of sustainability are the most addressed (Ma et al., 2018) in AM. LCA assessment and ecological labels are mostly used to evaluate the environmental aspects whereas technological advancement and LCC are used to access the economic aspects (Toniolo et al., 2019).

LCA and LCC are the commonly used tools to assess the features related to the environmental impacts, as well as the costs through the LC of components. An LCA is a methodological tool for measuring the environmental features of comparable products and processes. The results of an LCA can either be based on inventory results, aggregated impact categories or weighting to a single score (Böckin & Tillman, 2019). LCA methodology enables an industrial evaluation of the environmental dimensions of sustainability. This helps to identify the possible environmental impact of a single or comparable process, method or service based on input-output resources. LCA enables a systematic and reliable accounting of potential hotspots of processes on an equal scale. LCC is another systematic methodology that was used to evaluate LCC against the performance of metal L-PBF in the different LC phases. LC studies may be handled from 'cradle-to-gate' or 'cradle-to-grave'. The cradle-to-gate study is limited only to the production whereas the cradle-to-grave includes all phases of a product from raw material to end-of-life (EOL) (Ma et al., 2018).

The need to find new methods and ways of making optimised metal components with L-PBF to a satisfactory level of integrity and cost-effectiveness capable of enhancing sustainability propelled the initiation and successful completion of this thesis. AM was recognised as a feasible manufacturing method for metal components that could help overcome resources usage impacts, waste and emission creation. Few academic publications had conducted systematic studies that highlighted the aspects of sustainability of AM, especially metal AM. A lot of the existing studies at the start of this thesis showed the flexibility of AM in making lightweight and customised parts that could offer better functionality mainly with polymer materials (Huang et al., 2016). In a study, Huang et al. (2016) showed that many of the existing reviews only discussed the benefits and challenges in the production phase, thereby excluding the overall benefits throughout the product LC. Another observation from preliminary studies showed that the existing literature on the aspects of sustainability of AM was mainly published by proponents and opponents from a commercial perspective. A review on the CE in AM and especially L-PBF was showed only a few publicised studies. There was a lack of genuine academic research that could give an unbiased argument to support a fair judgment of these metal L-PBF from an LC. This thesis uses the LCA and LCC tools to evaluate the environmental and economic aspects of sustainability in metal L-PBF using both cradle-to-grave and cradle-to-gate scopes. This thesis aimed to fill in some of the gaps in the literature on the environmental and economic aspects of sustainability aspects and the CE of metal L-PBF.

Data from the literature showed that the method had limitations within the various subcategories, despite the benefits of making optimised components. Design optimisation using digital simulation tools in AM offers new ways of overcoming the shortcomings, such as low productivity (H. Lee et al., 2017), high process energy consumption, high costs and negative environmental impacts (Campbell & Bourell, 2020; Daraban et al., 2019). Currently, some of the key driving factors of metal AM are lower weight, customisation, increased energy efficiency, enhanced cost-efficacy, increased durability, reduced material consumption, minimised waste and emissions from idea generation through production, use and EOL.

This thesis comprises five publications (I, II, III, IV and V), which will subsequently and respectively be referred to as **P1, P2, P3, P4** and **P5**.

P1: Nyamekye, P., Leino, M., Piili, H., & Salminen, A. (2015). 'Overview of Sustainability Studies of CNC Machining and LAM of Stainless Steel'. *Physics Procedia*. Elsevier B.V., 78, pp. 367–376

P2: Nyamekye, P., Piili, H., Leino, M., & Salminen, A. (2017). 'Preliminary Investigation on Life Cycle Inventory of Powder Bed Fusion of Stainless Steel'. *Physics Procedia*. Elsevier B.V., 89, pp. 108–121

P3: Laitinen, V., Piili, H., Nyamekye, P., Ullakko, K., & Salminen, A. (2019). 'Effect of process parameters on the formation of single track in pulsed laser powder bed fusion', in *Procedia Manufacturing*. Elsevier B.V., 36, pp. 176-183

P4: Nyamekye, P., Unt, A., Salminen, A., & Piili, H. (2020). 'Integration of simulation-driven DFAM and LCC analysis for decision making in L-PBF', *Metals*. 10(9), pp. 1–20

P5: Nyamekye, P., Nieminen, P., Bilesan, M. R., Repo, E., Piili, H., & Salminen, A. (2021). 'Prospects for laser-based powder bed fusion in the manufacturing of metal electrodes: A review'. *Applied Materials Today*. Elsevier Ltd., 23(101040)

The first motivation for this thesis was to contribute to filling the identified research gap in terms of understanding the aspects of sustainability of AM (**P1** and **P2**). The second motivation was to identify ways to control and improve the processing to achieve the required functionality (**P3**). The third motivation of the thesis was to apply life cycle thinking to evaluate the potential lifelong benefits in contrast to the manufacturing phase inefficiencies (**P4** and **P5**). The principal motivation of this thesis was also to offer a critical fact-based contribution free of subjective or commercial considerations that would use both empirical and qualitative scenarios to support the sustainability arguments of L-PBF (**P2**). This was achieved with an LCI study performed as part of **P2** of this thesis.

All input energy, major input material, output product, recyclable waste and unrecyclable waste were identified and measured within the defined study boundary.

A comprehensive appraisal of the sustainability of AM and specifically L-PBF will deepen the understanding of the benefits that this method offers. L-PBF is a challenging manufacturing method of making metal components despite the potentially broader adoption to make efficient designs. L-PBF was selected in this thesis because the method has aspects that have not been fully understood as an emerging manufacturing method. The benefits that were considered ranged from supply chain (**P1**) material and energy consumption (**P2**), effect of process parameters (**P3**), influence of design for additive manufacturing (DfAM) and LCC (**P4**), as well as case examples of the potential benefits in other fields of application (electrochemical) other than the usually published applications **(P5**). Since the start of this study, L-PBF has changed over the years regarding technology and terminologies. Laser additive manufacturing (LAM) in **P1** and PBF in **P2** all refer to L-PBF. L-PBF is used consistently in **P3–P5** and in this thesis.

This thesis aimed to investigate the aspects of sustainability of metal L-PBF to identify and highlight ways of improving efficiency with data from reviews, case examples and experimental studies. Thus, using L-PBF to improve energy, raw material, time usage and waste has been prioritised. The focus of all the experimental studies was to identify the ways that L-PBF can enhance efficiency in manufacturing to support sustainable manufacturing and the CE. The objectives of this thesis were:

- **Objective 1 (O1)**: Investigate and perform experimental studies to evaluate the factors affecting the sustainability and the circular economy of metal L-PBF
- **Objective 2 (O2)**: Create a basic model of an integrated LCC-DfAM model that could highlight the overall benefits of metal L-PBF
- **Objective 3 (O3)**: Analyse, modify and verify the created LCC-driven DfAM model of metal L-PBF in the context of industrial engineering and business

1.3 Research questions of the study

L-PBF is a viable means to manufacture customised, cost-efficient and energy-efficient components while reducing waste and emissions. However, the method has some generic processing limitations such as high energy consumption, low productivity, low process speed, low dimensional accuracy, rough surface finish, (Ruffo & Hague, 2007) and process-induced defects. A lack of fusion, balling, keyholes, inclusions, thermal distortions and porosity are examples of intrinsic process defects that can occur during manufacturing (Foster et al., 2020; Saunders, 2017). Inclusions refer to foreign materials (NASA, 2019) that are trapped in the melt pool. This may be due to the powder feedstock characteristics or oxidation due to high working temperature (Fayazfar et al., 2018; Y. Sun et al., 2018). The formation of undesirable inclusion in components can negatively affect part performance and appearance. Thermal distortion and porosity may occur when a powder layer is exposed to excessive laser power density or low exposure speed (Foster et al., 2020). Thermal distortion occurs when the original shape is modified due to thermal stress caused by excess heat input or accumulated heat. The thermal forces during the process are typically those that cause problems during the process. Support structures can avoid distortion by acting as a heat sink and ensuring the adherence of parts to the build platform (Culleton et al., 2017; Menu, 2018; Praet, 2017). Residual stress is stress that remains in a part after the removal of the cause. This may typically not cause problems although propagation could lead to cracking (Fayazfar et al., 2018). Porosity is another defect in L-PBF that is either process or gas-induced. Hot isostatic pressing (HIP) can be used to rectify such defects to avoid potential fatigue failure that might occur during the use phase of the component (Metal Technology Co. Ltd, 2018). These defects could cause the failure of the build process or affect the reliability of components, create waste, require extra energy, raw material and incur extra costs to create new parts.

The question is how to determine the suitability of metal L-PBF in achieving sustainable manufacturing? How and how to evaluate the environmental, economic aspects of sustainability and circularity of metal L-PBF? Metal AM in this thesis refers to the use of metal powder/wire as feedstock (raw material) to make components. All comparable manufacturing method studies in these were based on metal AM/L-PBF and CNC machining (CNC machining). The main underlying research questions of this thesis were:

- **Research question 1 (R1)**: How can the factors that affect the environmental aspects of sustainability of metal L-PBF be experimentally evaluated from a life cycle perspective?
- **Research question 2 (R2)**: How does the application of LCC-driven DfAM optimisations in metal L-PBF influence the economic aspects of sustainability from a life cycle perspective?
- **Research question 3 (R3)**: Which overall model describes LCC-driven DfAM and how is this relevant to the industry?

The relationships between objectives, research questions and the corresponding publications (**P1**, **P2**, **P3**, **P4**, **P5**) are outlined in Figure 1.1. This figure also states that this thesis has been divided into three parts (**Part I**, **Part II** and **Part III**).

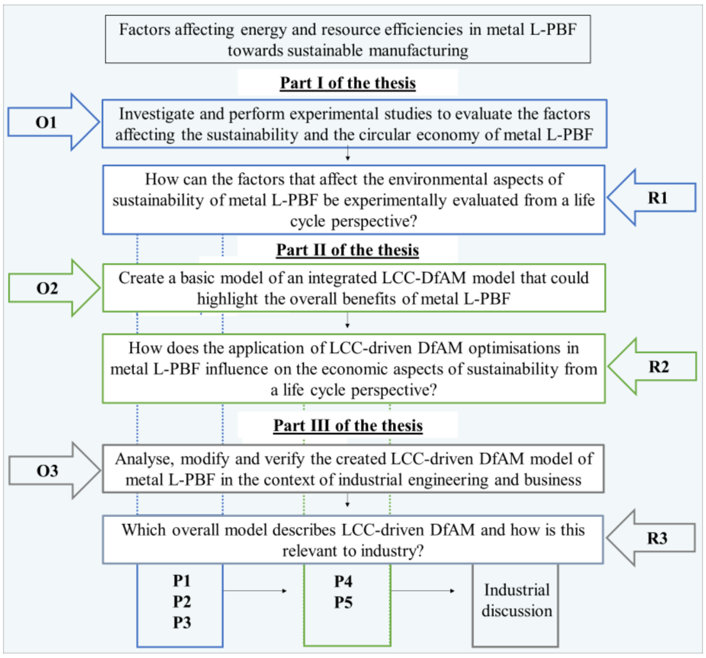


Figure 1.1: Representation of the relationship between the objective research questions of the study and the publications of this thesis.

The relationship of the objectives, research questions and the five publications forming this thesis are grouped according to colour, as shown in Figure 1.1. The initial input data to **Part I** of the thesis were 'to identify the factors that affect the efficiency of metal L-PBF towards sustainable manufacturing'. The **Part II** of the thesis was developed based on the identified needs from the completion of Part I. The results of **Part II** necessitated the need to verify and validate the developed LCC-driven DfAM model from an industrial perspective. The **Part III** of the thesis was carried out as a systematic application of the developed LCC-driven DfAM model to enhance suitability in the industrial sector. Refer to Appendix D for the relationship between research objectives, questions and publications.

1.4 Scope and limitations of the study

This thesis investigates the sustainability aspects of AM/L-PBF in terms of resource efficiency, cost efficiency, waste and emissions reduction. The thesis was limited to only metal AM, specifically to L-PBF. All the related studies, reviews, case examples and experiments presented only include L-PBF manufactured metal components. This thesis concentrates on L-PBF as it is one of the most widely used metal AM technologies due to its accuracy. A general account of metal AM has been included to distinguish between the various AM techniques that can be used to make metal components. A study of the various phases a component undergoes from idea inception, manufacturing, use to EOL has been performed to support decision-making regarding the adoption of L-PBF. The LC phases considered in this thesis and areas of consideration for the various studied topics are illustrated in Figure 1.2.

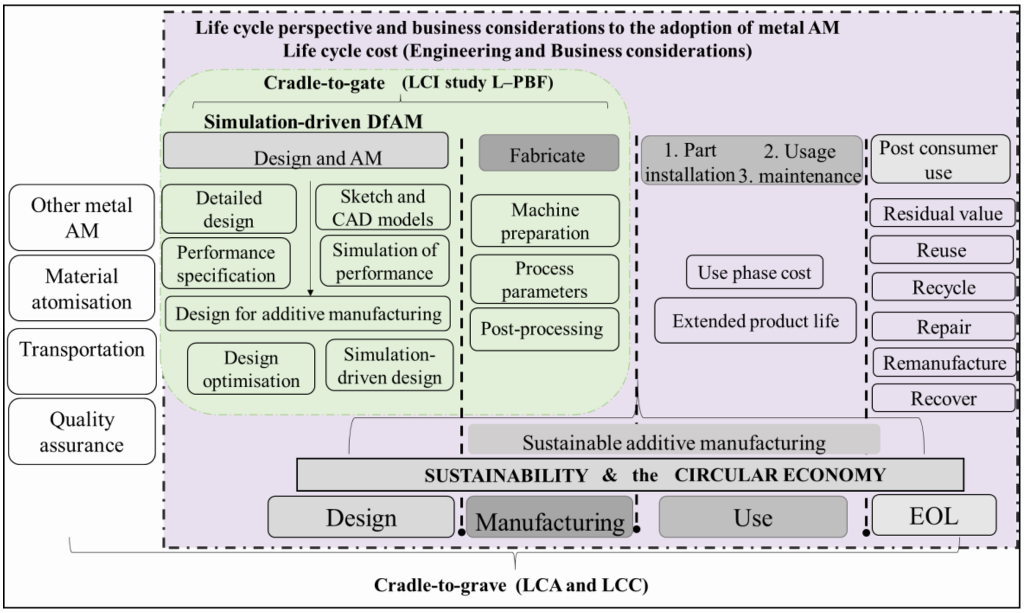


Figure 1.2: Representation of the scope of the study.

Figure 1.2 shows the various LC phases and scope of the study carried out in this thesis to find answers to **R1**, **R2** and **R3**. The scope of the numerical data inventory and interpretation was limited to design and production. A proposed plan for further studies that would have included the powder procurement and use phases did not materialise during this thesis due to a lack of resources and funding. LCA/LCI by nature has its limitations as no single study can encompass all the scenarios. The results of the LCI in this thesis can be applied to interpreting similar experimental set-ups. This thesis was designed and executed following current trends and available resources. The business case gives an overview of how value chain and strength, weakness, opportunities and threat (SWOT) analyses can be applied to L-PBF to support decision-making. No practical application of this has been conducted in this thesis through a scenario-based analysis of the applicability of these business models in metal AM have been discussed from an industrial perspective.

LCI in this thesis included the inventorying of input metal, energy, process liquids and losses resulting from chips and powder removed as waste. LCA by nature has its limitations as no single study can encompass all the scenarios. The results of this LCI in this study, however, can be applied to make interpretations of similar experimental set-ups. The results based on experimental and theoretical studies only can be supposed as same for similar cases. Figure 1.3 illustrates the steps of LCA according to ISO 14040. The region shown in green shows the steps included in the LCI study carried out in this thesis.

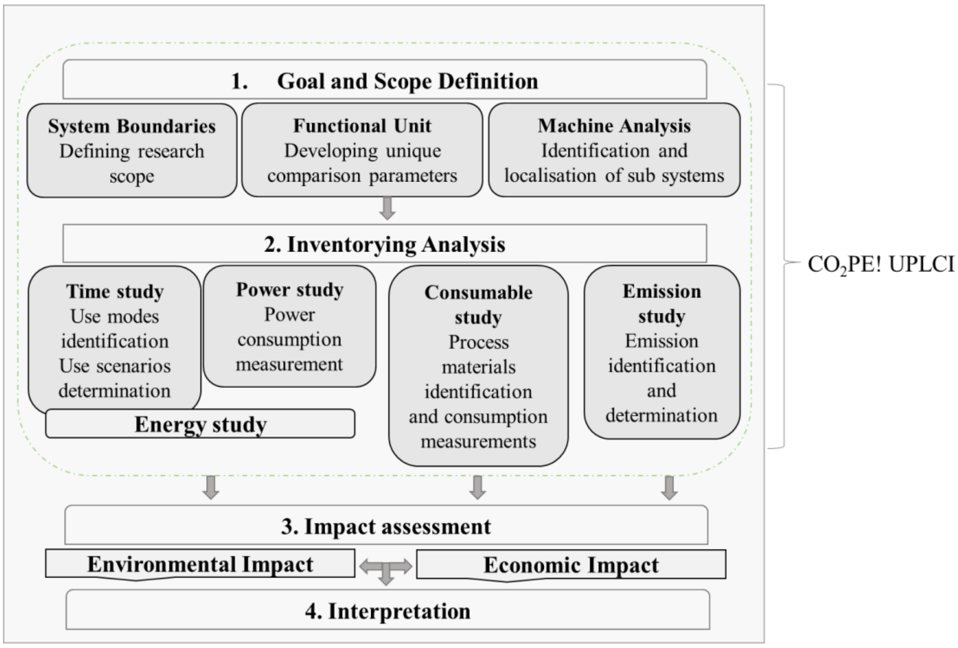


Figure 1.3: Representation of the steps of LCA (ISO, 2006) and the steps of CO_2PE! UPLCI included in this thesis.

The LCA study was applied only at the inventory phase, to study the energy efficiency, material consumption, created waste and emissions, thus the impact assessment and interpretation were omitted.

1.5 Structure of the study and thesis overview

The thesis consists of three parts and each part answers one research question to achieve correlative objectives. The three parts of the thesis are:

- **Part I**: The recognised need for research and development in the sustainability of L-PBF for metal components
- **Part II**: The recognised need for the LCC-driven DfAM model
- **Part III**: The recognised need for an overall industry-relevant LCC-driven DfAM

Part I included an experimental LCI assessment of L-PBF in comparison with CNC machining. The final study in **Part I** included experiments testing on process parameters and their effect on scan track formation. The results of these studies were published in **P1**, **P2** and **P3** respectively. **Part II** presented a state of the art of DfAM and LCC, the factors that influence cost from idea conception to EOL. The review and summary of relevant existing academic and industrial cases were used to highlight the lifetime cost savings offered by L-PBF. This part also focused on the technical application of DfAM guidelines and design optimisation to reduce overall inefficiencies which were needed to enhance the technological productivity. The result of this study led to the creation of the preliminary LCC-driven DfAM model. **Part II** also verified the potential to reduce electrochemical process inefficiencies through optimised L-PBF separation units. The results of **Part II** were published in **P4** and **P5**. **Part II** focused on the technical application of DfAM guidelines and design optimisation and their influence on the overall resource efficiencies, waste and emissions reductions. The studies performed as part of **Part II** were needed to enhance the technological productiveness and effectiveness of metal AM/L-PBF. **Part III** discussed L-PBF and the way the process can be used to achieve sustainability and the circular economy from the industrial perspective based on the result of **Part I** and **Part II**. This section included considerations of industrial relevance and offered a systematic approach to refine the developed model. **Part III** was used to draw conclusions of this thesis and give recommendations for further studies. An illustration of the thesis structure is shown in Figure 1.4.

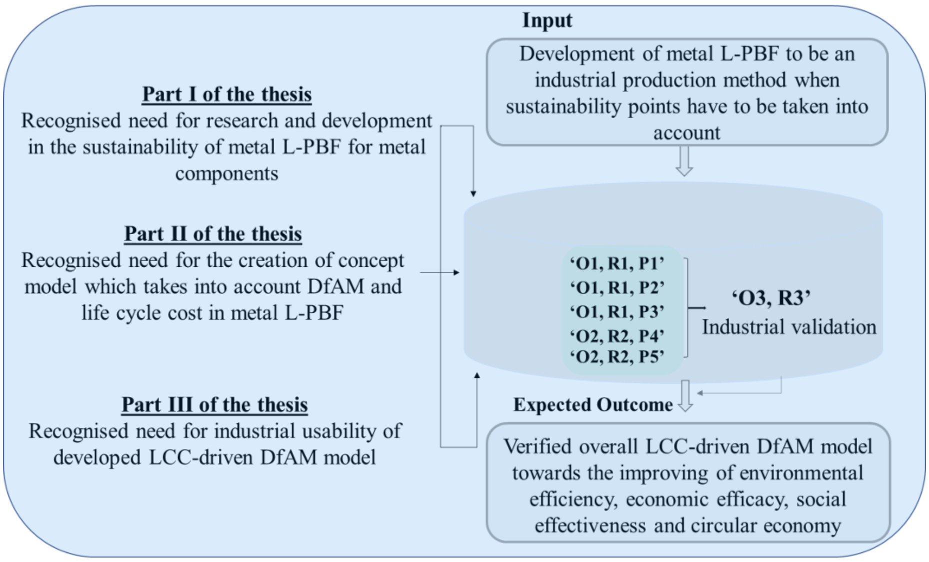


Figure 1.4: Summary of thesis structure with the flow of activities that were used to achieve the main results and conclusions.

Each of the parts answers one of the three research questions of the thesis. Figure 1.5 illustrates the structure of the study based on the identified needs, research objectives, research questions, as well as the inputs/outputs to achieving **P1**–**P5**. The initial input was to support the development of L-PBF as an industrial production method by assessing the sustainability aspects. The outcome of this thesis is a verified overall LCC-driven DfAM model and its principles for evaluating the sustainability in metal L-PBF (environmental efficiency and economic efficacy).

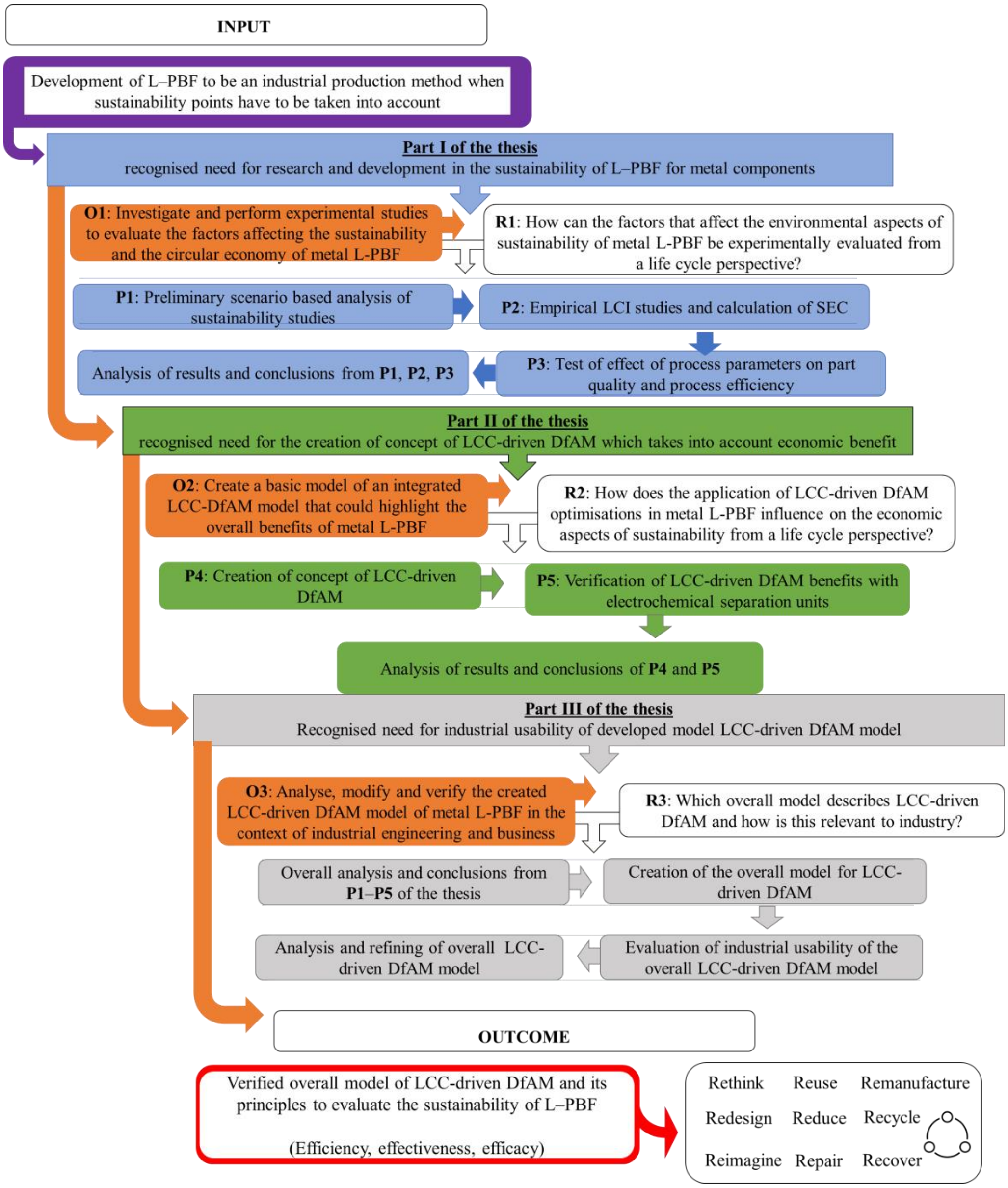


Figure 1.5 A representation of the detailed structure of the thesis from initial input to final output.

Figure 1.5 shows how the various parts of the thesis contributed to the studying of sustainability aspects especially in terms of environmental efficiency and economic efficacy in metal L-PBF. A representation of a detailed structure of the thesis is shown in Appendix F.

1.6 Methodology

The thesis investigates, evaluates and analyses the aspects of sustainability of L-PBF in providing a useful tool for decision-making processes. Systematic qualitative and quantitative methods were used to gather data to ascertain the aspects of sustainability in metal L-PBF, i.e., the economic and environmental aspects. The environmental impact throughout the LC of components made with L-PBF was studied to identify how the method supports sustainable manufacturing. Qualitative studies included theoretical scenarios and case studies regarding the application of simulation-driven DfAM, LCC analysis, as well as a review of the prospects of metal L-PBF in electrochemical applications. An electrochemical process is a chemical process that involves the transfer of electrons in an aqueous solution via the release of chemical energy or external voltage.

The research methodologies used in the publications of the thesis are summarised in Figure 1.6.

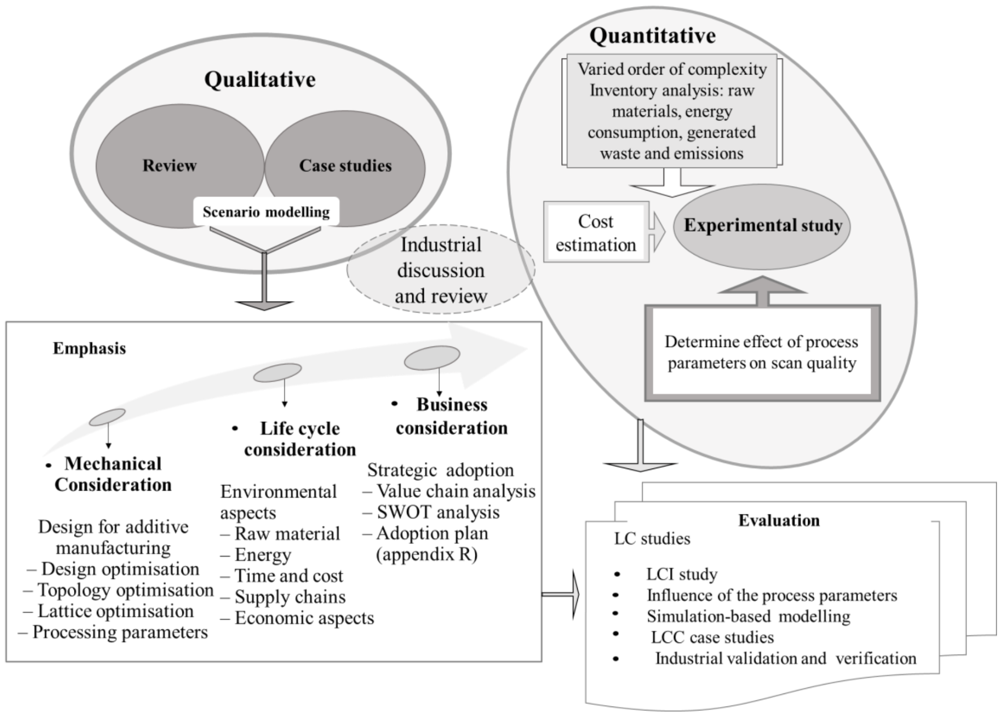


Figure 1.6: Schematic overview of the methodologies used in the thesis.

Figure 1.6 illustrates both the theoretical and practical methods used to investigate the sustainability issues in metal L-PBF.

Methodologies '**O1**, **R1**': There were three studies as part of '**O1**, **RI**', the methods and results respectively published in **P1**, **P2** and **P3**. The initial studies in **P1** presented an introductory background of sustainability and L-PBF. A preliminary supply chain scenario of L-PBF was used to evaluate sustainable aspects. The different supply chains of L-PBF and CNC machining were compared using scenario used cases from raw material acquisition to product end-user. The **P1** of the thesis included collected data from the literature on the sustainability issues of AM compared to CNC machining. A scenario-based case study of the life cycle stages including raw material (powder and billet) of both methods, manufacturing and interlinking transportation were considered in terms of CO_2 emissions.

The experimental studies in **P2** were carried out as a comparison of L-PBF and CNC machining. LCI methods and component complexity scenarios were used to investigate and to find out evidence about how environmental impacts can be evaluated in L-PBF and CNC machining. Component complexity scenarios mean that geometries were designed to have increased manufacturability as a basis of comparison. The LCI study was performed as an inventory of inputs/outputs for metal L-PBF and CNC machining. A measuring scale was used to measure the weight of stainless-steel powder and bar. Siemens Sentron PAC 3200 was used to measure the power consumptions. The measuring device offered precise and reliable power values from all individual electrical consuming units. The measured power values and time consumptions were used to calculate energy values. The specific energy consumption (*SEC*), raw material consumption and amount of waste in both processes were compared. SEC (kWh/kg) is a ratio of the energy consumed (kWh) to the unit mass (kg) of produced components.

The study in **P3** investigated the formation of single tracks, the process phenomena and the effects of associated process parameters. The study aimed to understand the potential of pulse wave emissions in the formation of fine-feature (for example) thin walls. The study in **P3** compared the quality of L-PBF(P) and L-PBF(CW) manufactured components using stainless steel 316L. A modified trial L-PBF system with IPG ytterbium fibre laser (wavelength 1075 nm, maximum average power 200 W) was used for the L-PBF(CW) and L-PBF(P) experiments. The laser power used for the L-PBF(P) experiment was 30–190 W and a constant average (peak power) of 20 W was used in the L-PBF(CW) based on predefined parameters. Examples of the process parameters used in this study included pulse length (t_p), layer thickness (t), scanning speed (V), laser power (P), hatch distance (Δ_{ys}) and volumetric energy density (*VED*). Layer thickness refers to the distance in terms of the height of the successive addition of powder material in the layer height of each successive addition of material. Scanning speed refers to how fast the mirrors of the scanning system can move and how fast the laser beam deflects. Hatching distance is the distance between successive laser passes. Volumetric energy density refers to the energy input to a material. Pulse length refers to the duration of laser exposure when the pulsation option of scanning is used. Laser power refers to the optical power output of the laser beam, which is either a continuous exposure of constant average (peak) power output in continuous wave (CW) processing or the pulsation wave (P) of an alternating power value. The experimental study also compared the effects of a pulsed wave with normal continuous-wave emissions in the L-PBF process. The majority of current L-PBF are based on L-PBF(CW). This study was done to investigate the potential influence of pulsed laser on processing and part quality to control part quality and processing efficiency.

Methodologies '**O2**, **R2**': Two studies were carried out as parts of '**O2**, **R2**'. The methods and results were published in **P4** and **P5**. A review was performed in **P4** on DfAM, simulation software and LCC of L-PBF manufactured components. The study was performed to identify the state of the art of benefits of digital tools and how they can be used with the right design rules to control overall costs along with the LC phases of metal L-PBF components. An integrated study of these approaches was used to investigate the benefits of simulation-driven designs in reducing the overall costs in L-PBF. Simulation-driven design refers to the use of digital tools to simulate and automate product design based on input data of the performance requirements and the intended functionality. Integration of an initial simulation-driven DfAM and LCC-driven model was created as part of this study. The review and scenario study with existing industrial cases were used to highlight the lifetime cost savings offered by metal AM/L-PBF. This was conducted to highlight the influence of design optimisation via the use of simulation-driven DfAM. An experimental evaluation of the practicality of DfAM with a used and EOL case would have provided a better understanding of how simulation-driven DfAM can affect LCC in metal AM/L-PBF. Due to the lack of such a study, the implications from an economic perspective were analysed with a computer model with data from an existing industrial case. The LCC study was used to quantify costs based on an evaluation of the impact of energy, material and time on productivity.

Data from the literature were used to investigate the possibility to enhance electrochemical performance offered by digital tools and metal L-PBF in **P5**. The study also investigated the possibility of multi-materials and cost efficiency with review data. Optimised designs and their influence on improving resources consumption, performance and costs efficiencies throughout the LC phases (design, manufacture, use, EOL) were investigated. was carried out as an application of the created LCC-driven DfAM model. Reviews were performed to identify data to support how digital tools can create optimised L-PBF metal electrodes potentially enhance electrochemical separation performance and costs efficiencies.

Methodologies 3, '**O3, R3**': The final method of the thesis was carried out as discussions with industrial representatives on the usability of the created integrated LCC-driven DfAM model which was the main outcome of this thesis. The discussion centred on the environmental and economic benefits of metal AM/L-PBF to original equipment manufacturers (OEMs). The initial created integrated simulation-driven DfAM and LCC-driven DfAM model in **P4** was modified based on results of the discussion to carter for industrial considerations.

1.7 Expected results of the study

The expected result of this thesis was to identify ways by which metal AM can enhance sustainability and the CE. It was to identify means by which environmental efficiency, economic efficacy and social effectiveness could be achieved via AM. Environmental efficiency in this thesis refers to how well a manufacturing method utilises energy and raw material to satisfy functionality and performance with reduced waste. Economic efficacy is the successful use of products and processes to achieve productivity and cost-efficiency. These efficiencies also refer to the technological factors that enhance the longevity and performance of components in respect of environmental and economic performance which correlate to the CE. Social equity effectiveness refers to the ability to successfully provide continuous and balanced resources for the well-being of personnel, equal access opportunities to available resources and machinery. This also includes the ability to identify, comprehend and attain effective social networks that can create the motivation to produce benefits and commitment within an organisation. A schematic overview of the expected results of this thesis is outlined in Figure 1.7.

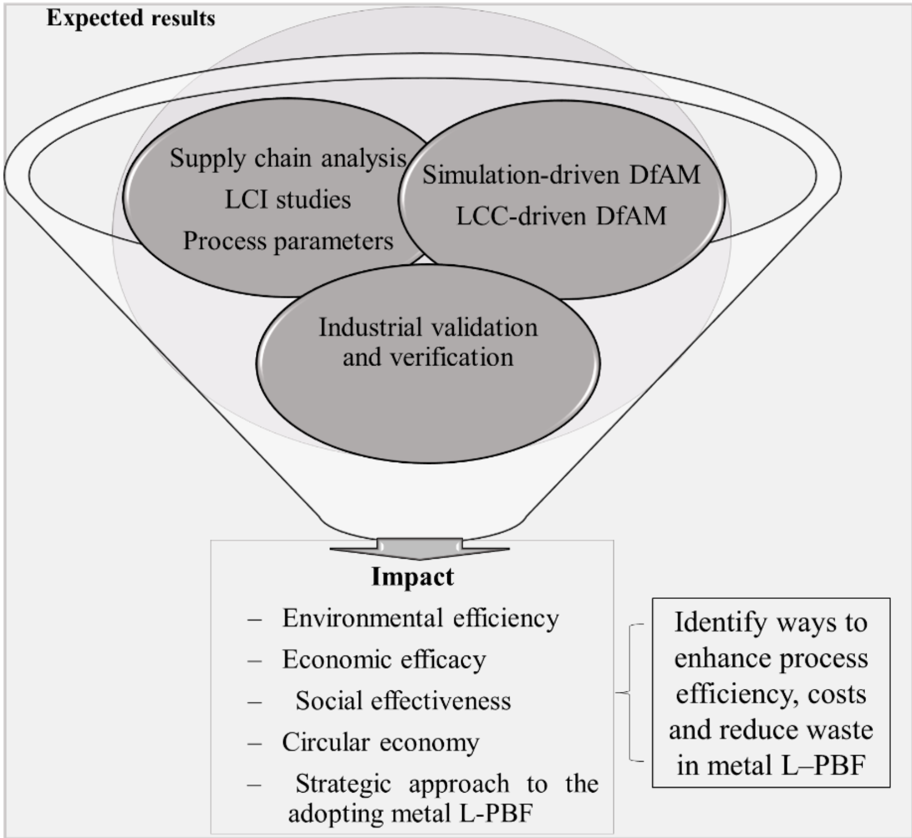


Figure 1.7: Representation of the main expected results and contributions of the thesis.

Figure 1.7 shows the planned methodology to study aspects of sustainability in metal AM/L-PBF and to identify contributions of metal L-PBF that supports sustainable manufacturing. The expectation was that the work would serve as a basis for other similar sustainable manufacturing-related research to support decision-making and the acceptance of L-PBF as well as other AM methods. This thesis presents a model that can be used to determine the overall LC benefits of metal L-PBF, rather than just from the manufacturing phase. Given this, L-PBF potential to improve energy efficiency, raw-material consumption, time usage, waste and emissions reductions were prioritised.

2 Sustainability and additive manufacturing

According to Brundtland's report (1987), sustainable development is defined as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (Brundtland, 1987). The goals of sustainable development have promoted collaborations within the sciences, engineering and commerce at various levels in the industrial sector. These kinds of collaborations have paved the way for novel studies within different research institutions on sustainability and additive manufacturing.

It was anticipated that the rapid growth in the research of sustainability and the CE in AM would overcome certain aspects of the inherent process limitations and highlight the most optimal utilisation approaches. A comparison of review data was performed at the beginning and end of November 2020 on aspects of sustainability and the CE in metal AM. The keywords used for gathering these data were ("additive manufacturing" OR "3D printing" AND sustainability), ("additive manufacturing" OR "3D printing" AND metal AND sustainability), ("additive manufacturing" OR "3D printing" AND "circular economy") and ("additive manufacturing" OR "3D printing" AND metal AND "circular economy"). The review considered four document types: research articles, review articles, conference articles and review articles at conferences. Figure 2.1 shows the number of publications on sustainability and circular economy extracted from the SCOPUS database.

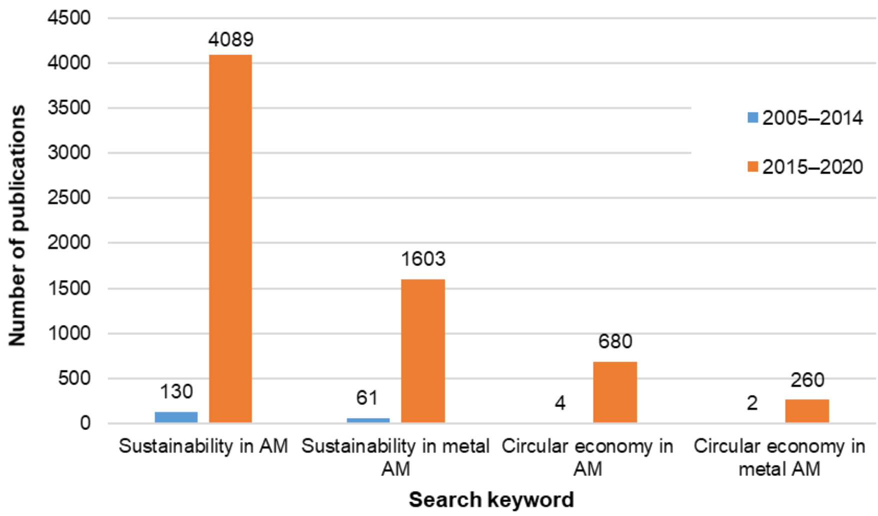


Figure 2.1: Representation of growth in research into sustainability and the CE (November 2020).

Figure 2.1 illustrates that studies on sustainability and AM generally have increased for the comparable time ranges. The growth in research can be seen to be developing for all the considered topics. As it is shown in Figure 2.1, few studies have been carried out in metal AM compared to the total performed studies. However, this is not in compliance with reality as most of the existing publications do not distinguish between the different AM subcategories or material. The forecast for a rise in sustainability and the CE studies has been proven and this growth is expected to continue as AM becomes part of mainstream manufacturing and the educational curriculum. AM offers multi-material (dissimilar materials) manufacturing possibilities with enhanced functions and cost-effectiveness in support of the environment and economic aspects of sustainability. These aspects of AM present new research topics to be explored by both the academic and industrial sectors. Currently, AM is one of the advanced technologies that has created new research areas in Science, Technology, Engineering, Arts and Mathematics (STEAM) (Colorado et al., 2021). Undoubtedly such studies will foster the continuation of the exploration of this new technology to a broader field and identify ways of overcoming some of the inherent process inefficiencies and identified gaps in the literature.

2.1 Sustainability

There are three dimensions of sustainability, (i.e., environment, economic and social) known as the three pillars of sustainability. The study of sustainability is evolving. So has the traditional model of sustainability as an intersection changed into an integrated model of the three dimensions (economy, social and environmental) (see Appendix G). The classical model of intersection depicts the equal importance of the three aspects. The integration model depicts that environmental protection leads to the safety of people, products and community to making of profits. The integrated model can be interpreted in such a way that the environmental (planet) is the most contributing aspect of sustainability that encompasses the social equity (people) and the economy (profit). The acceleration in the adoption of material and energy-efficient technologies offers an innovative way of boosting resource efficiencies, increasing productivity, decreasing waste and emissions. The efficient use of materials and processes in sustainable manufacturing provides a competitive edge that could potentially be utilised to increase sales (US EPA, 2020).

The sustainable development goals (SDGs) provide a shared blueprint for all United Union (UN) member states to achieve a better sustainable future in different aspects including people, the planet, prosperity, peace and partnership by 2030. Among 17 SDGs (United Nations, 2020a), five can be closely linked to manufacturing. These five goals are (1) affordable and clean energy, SDG 7, (2) Decent work and economic growth, SDG 8, (3) industry, innovation and infrastructure, SDG 9, (4) responsible consumption and production, SDG 12 and (5) climate action, SDG 13. Some of these goals seek to create economic productivity through diversification, productive activities, creativity and innovation, technological upgrading and innovation, renewable energies, energy-efficient processes, systems and materials, efficient use of resources and creating innovations that reduce emissions to combat climate change (United Nations, 2020b; 2020c; 2020d; 2020e; 2020 f). Industrial companies can use the basic three bottom-line approaches of sustainability to achieve SDGs for the planet, people and profit (Idowu et al., 2014) as illustrated by Figure 2.2.

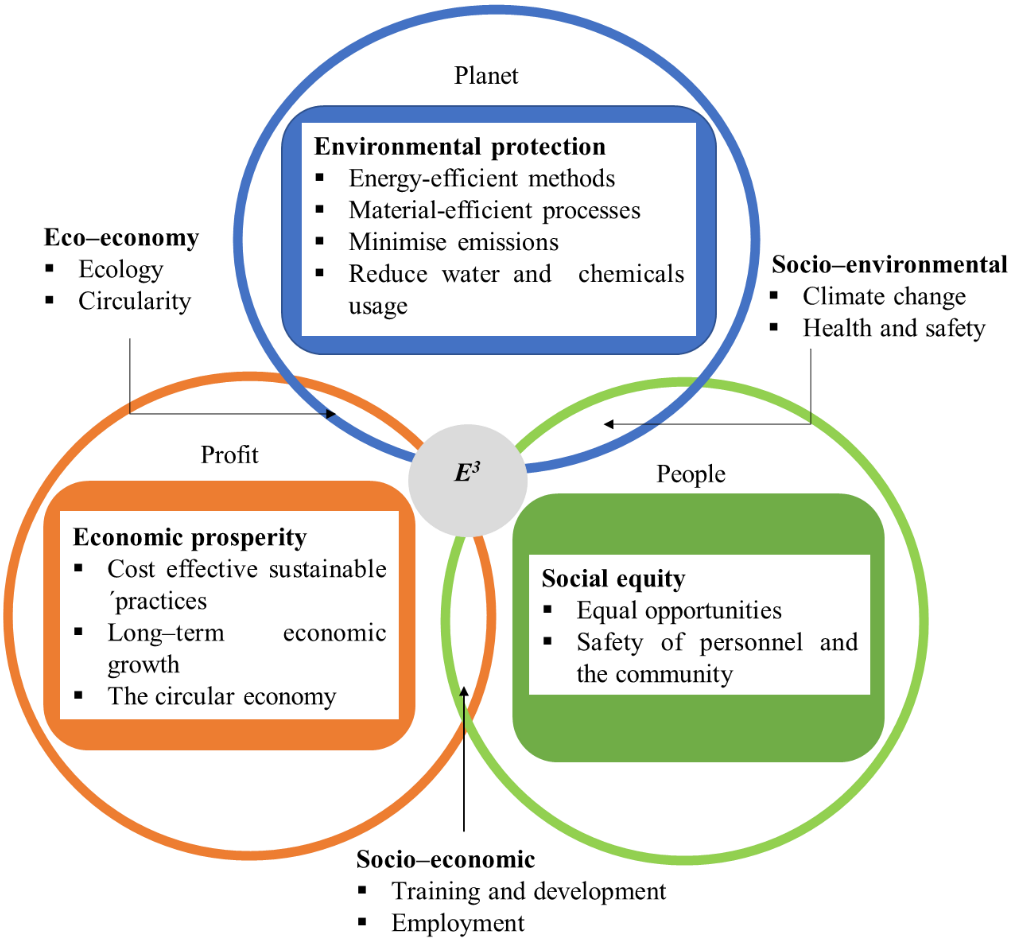


Figure 2.2: Representation of three bottom line approaches to sustainability with respective contributions to sustainability.

Figure 2.2 shows that sustainability can be achieved when all three sustainability aspects; environment, economic and social, are fulfilled as represented by E^3. The current development in sustainability has made it almost impossible to distinguish the three pillars as they closely intertwine with each other. The integration between the planet, people and planet can drive value creation within companies (Bergmans, 2006; de Brito & Terzieva, 2016). The framework used for sustainability evaluation largely determine the integration (Büyüközkan & Karabulut, 2018).

2.1.1 Sustainable manufacturing

Manufacturing methods have to meet certain SDGs to be characterised as sustainable. According to Salonitis & Ball (2013), manufacturing processes are defined as *the processes that transform materials and information into goods for the satisfaction of human needs*. Manufacturing systems often use large volumes of raw material and energy to make goods (Brundtland, 1987), which often are characterised by the release of pollutants. The released pollutants are either emitted from the manufacturing process or from secondary systems such as the energy used to produce raw material and run manufacturing machines. Various industrial activities are centred on the creation of products and services (Brozović et al., 2020) that require natural resources as inputs. The goal of manufacturing companies is to make profits from the goods and services they provide.

The concern about diminishing resources and increased emissions became part of the influencing factors that helped companies make sustainable choices. Some manufacturing companies in the past regarded any response to environmental concerns to be a financial burden that often resulted in additional expenditure. These companies had to compromise on harming their business while protecting the environment or inversely harming the earth while maintaining or increasing productivity. The decreasing of the quantity of resources used per product and reducing the overall volume of waste and emissions remain a concern in the manufacturing sectors. Investing in employees and making them part of the decision-making process when it comes to new changes, will foster trust and commitment (Vance, 2006) to get goals. Having committed employees will reduce employee change over which often require a significant financial outlay on recruitment and training. Such strategic improvements could enhance the environmental benefits, cost savings, social equity and offer well-balanced operations with a proper level of safety for the employee, community and product (US EPA, 2020).

The development of sustainable manufacturing helped to create a balance between the environment and the economy for mutual benefit. Early adopters of sustainable manufacturing were able to discover innovative methods that created new market opportunities and increased economic growth (Clarke et al., 1994; US EPA, 2020). An increasing number of sustainable business practices enable manufacturers to create products that result in substantial financial and environmental benefits. Such practices promote ecological and economic methods that can reduce negative environmental impacts by conserving natural resources. The adherence to regulatory constraints and the identification of new market opportunities is seamlessly associated with sustainable manufacturing (US EPA, 2020).

Companies that adopt sustainable practices also benefit from gaining the trust of employees and customers (Impact Garden, 2020). The safety of personnel and the community can be enhanced through socio-environmentally sound methods of adhering to sustainable manufacturing principles. Companies can protect and strengthen their brand and reputation by adopting sustainable principles. The right measures must be identified and used to ensure all stakeholders remove any scepticism to avoid any resistance, this will encourage inclusiveness and commitment to achieving corporate sustainability goals. Increasing the knowledge of people by explaining the rationale behind sustainable manufacturing and aligning them with the personal values of employees are examples of ways of committing employees to set sustainable goals. The implementation of a co-created sustainable business with stakeholders creates better engagement among personnel, fosters employee retention and increases productivity (Idowu et al., 2014; Impact Garden, 2020; Polman & Bhattacharya, 2016).

LCA may not be applicable at the early product design stage as the needed data are often collected from the actual manufacturing phase. This often will mean changes to enhance sustainability aspects can only be achieved with redesigning and reproduction. This inherently present limitation with the use of LCA in AM. Yi et al., (2020) in a study have shown that prior evaluation of the sustainability in AM is possible during the design phase with energy performance assessment. The framework uses data from a simulation tool for energy consumption prediction, an assessment model for energy performance and general workflows of eco-design for AM (Yi et al., 2020).

2.1.2 The circular economy

The need to finding ways of increasing productivity and reducing waste and emissions becoming a focus in the present industrial era. In recent years, much attention has been paid to how well a manufacturing process can turn raw material into useful outputs through reduced usage of resources and minimal release of waste and emissions. The current goals of sustainable manufacturing are also about extending product life, minimising waste and emissions. The quest for competitiveness through increased resource efficiency, waste reduction and productivity are some of the driving forces to this industrial revolution (Salonitis, 2016; Ustundag & Cevikcan, 2018). Refer to Appendix B for an overview of the evolution of AM and the industrial revolution.

Current and emerging manufacturing and management aims are to preserve natural resources, omit waste and reduce emissions. The generally recognised ‘three R’ (3Rs) approach to the CE has evolved with the three additional ‘Rs’ in agreement with earlier proposals. Jawahir & Bradley (2016); Kishawy et al. (2018) proposed that the inclusion of recycling, remanufacture and recovery would help close the circular loop of raw material and only then could a truly CE be achieved in support of sustainable manufacturing. The current elements of the CE are based on the extension of a traditional model, 3R which are reduce, reuse and repair. All six elements enhance circularity with efficient raw material utilisation, waste reduction, extended product life, the recovery of raw material/energy after the useful life of components and minimising of emissions. Levers such as waste reduction, product life extension and material recovery (circularity) provide an effective way to mitigate the impact of material usage (Olivetti & Cullen, 2018). The elements of the CE that enable and create sustainable manufacturing may be affected by the choices made during the components designing or the inherent characteristics of the manufacturing methods. Figure 2.3 illustrates the preferred circularity to a closed-loop material flow.

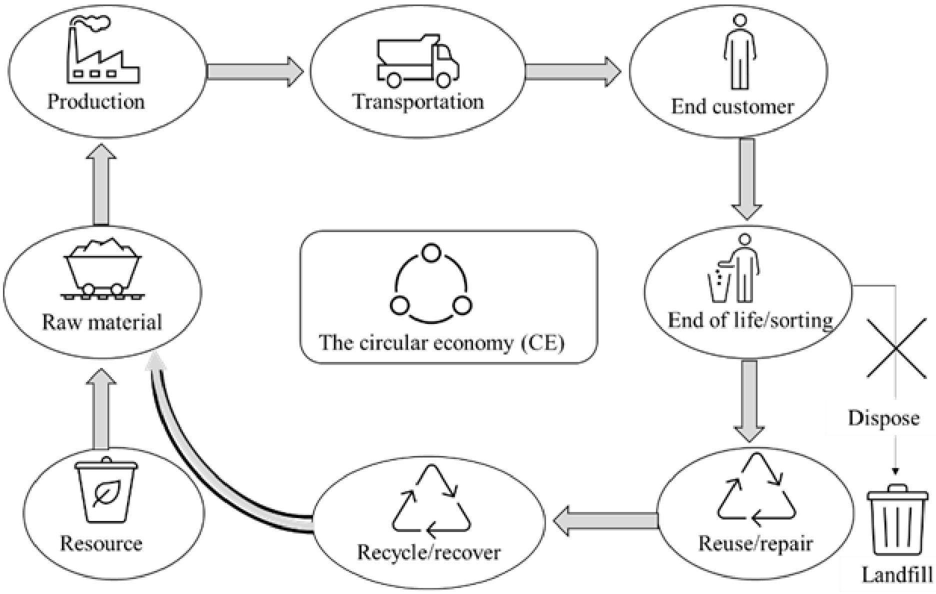


Figure 2.3: Representation of the circularity of products/materials in the CE.

Hibbard (2009); Kishawy et al. (2018); Olivetti & Cullen (2018) have highlighted certain enabling levers that can be used to achieve sustainable goals in the manufacturing sector. These levers are primarily and also characteristics of the CE, which are comprised of:

- Reducing energy consumption and using sustainable energy sources
- Reducing or eliminating waste to decrease the quantity of pollutants and toxins entering the ecosystem
- Increasing the longevity and performance of components, thereby reducing parts replacement
- Making reliable and qualified components that reduce raw material and energy consumption that would otherwise be used to replace failed components
- Reducing production cycle time
- Reusing, repairing, remanufacturing components (post-consumer use), whenever possible to reduce the need to produce new components
- Recycling waste, if possible, to reduce the uptake of virgin (new) raw material
- Recovering energy during the manufacturing phase to generate heat

Manufacturing methods that can reduce waste, process liquids, improve material utilisation through the reuse of raw material, downsizing and recycling of waste during the LC are potential ways to enhance the CE. The use of metal L-PBF inherently promotes the CE. Computer-based methods can be used to design and simulate performance and the manufacturing process. Optimised components can be achieved by rethinking, reimagining and redesigning the product design for energy-efficient, resource-efficient and cost-effective products while reducing negative impact to the ecosystem service. The consideration of material dispersion, process speed and temperature, can affect the sustainability aspects in AM (Ma et al., 2018). This approach to product design helps reduce time, raw material, energy consumptions, avoid waste and reduce emissions during the LC phases.

2.2 Additive manufacturing

The international standard organisation (ISO/ASTM 52900-2015) categorises AM into seven subcategories. The acronyms and definitions for the seven subcategories of AM used to build components layer by layer are:

- **Powder bed fusion (PBF):** is an AM process in which thermal energy selectively fuses regions of a powder bed
- **Binder jetting (BJ):** is an AM process in which a liquid bonding agent is selectively deposited to join powder materials
- **Material jetting (MJ):** is an AM process in which droplets of build material are selectively deposited
- **Directed energy deposition (DED):** is an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited
- **Material extrusion (ME):** is an AM process in which material is selectively dispensed through a nozzle or orifice
- **Sheet lamination (SL):** is an AM process in which sheets of material are bonded to form a part
- **Vat photopolymerisation (vat):** is an AM *process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization* (ISO/ASTM, 2015)

AM can print any shape in a vast range of materials including metals, ceramics (Gonzalez et al., 2016), thermoplastic composites (Parandoush et al., 2017), polymers and cement (Tofail et al., 2018). The different materials suitable for AM can vary in form, for example, powder (Alrbaey et al., 2014), wire, liquid and sheet (Vyatskikh et al., 2018) depending on the specifics of the applied AM technique. AM can be used to manufacture unique components using functionally graded materials (Ma et al., 2018), biomaterials (Bose et al., 2018) and nanomaterials (Challagulla et al., 2020) of single or multi-material composition (Dassault Systèmes, 2020; Puerto, 2015; Putra et al., 2020). A multi-material mixture can be used as an input material in L-PBF to achieve such multi functionalities (Putra et al., 2020). Multi-material AM is when the final component comprises more than one dissimilar material. The material mixture could be, for example, metal-metal and metal-ceramic (Putra et al., 2020; Wei et al., 2021).

The various AM subcategories differ from each other, for example, in terms of technological principles, process layout, form and type of materials, part resolution (OECD, 2017), need for a vacuum in the chamber, melting or bonding mechanism for materials and component size. The different AM subcategories begin and end in a similarly sequential manner. The sequential process flow for producing components with AM are shown in Figure 2.4.

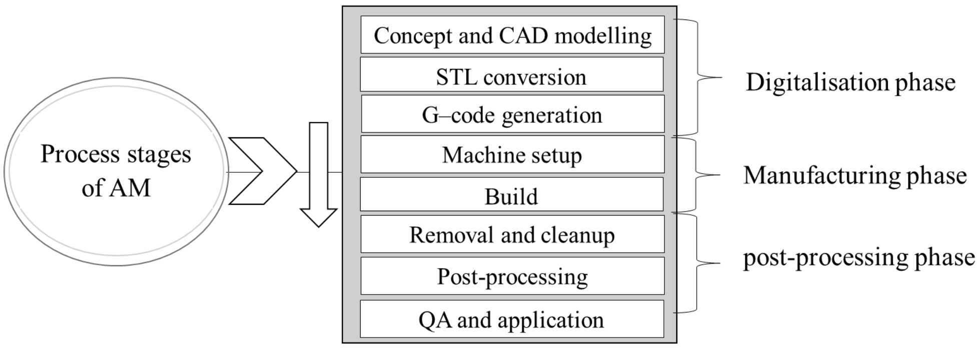


Figure 2.4: Representation of the main stages of AM.

The main stages of AM as shown in Figure 2.4 can generally be classified into digital, manufacturing and post-processing phases. Idea generation, scanning or CAD modelling of the design form the starting point of all the AM subcategories. The 3D model file is converted into STL format, which is then sliced into a two-dimensional (2D) format. Specialised software is used to generate the readable G-codes needed to effectively print the components on a machine (Ganesh Sarvankar & Yewale, 2019; Jiménez et al., 2019; OECD, 2017). Machine set-up includes the selection of process parameters, part placement in the build space, support generation, to mention a few. The build describes the actual layer-wise building of the components on an AM machine, followed by the removal and cleaning of the printed parts. This is followed by post-processing such as heat treatment machining or polishing of the as-built parts (Gibson & Khorasani, 2019; Maamoun et al., 2018) to improve the properties of the final parts. Improvements such as surface quality, mechanical properties, dimensional accuracy and others are conducted in the post-processing phase according to the defined properties and the required final quality.

The advancement of AM is the result of several successful improvements made by companies and researchers towards improving process efficiency. The expiration of previous patents in 2010 that prevented wide adoption of AM also paved the way for innovation that have supported the current expansion of AM (AMPOWER,2019; Thompson et al., 2016). New market opportunities with increased machine sales were recorded in 2013. The automobile industry is one of the industries that has supported the development of AM as an early user, primarily for concept design and prototypes in the late 20th century (see Appendix B1) at the start of AM commercialisation (Campbell &

Bourell, 2020). AM has emerged as a novel method in different sectors as the technology grows (Campbell & Bourell, 2020; Tashi et al., 2019; Thompson et al., 2016). The academic sector has also exhibited a growing interest in AM related studies (Campbell & Bourell, 2020). Refer to Appendix B2 for the fields of application and market trends of AM. However, like any manufacturing technology AM has some drawbacks that have prevented the advancement of AM, for example, lack of process-specific standards and specifications for materials and processes that are vital factors to material characterisation systems. Lack of standards in evaluating consistency and repeatability of the manufactured part using AM harmonisation (Monzón et al., 2014).

The absence of standardised qualifications or certifications is a potential threat, particularly in the aerospace, automotive and medicine sectors in which precision is essential (DNV GL AS, 2017; EOS, 2020a; Hinebaugh, 2018; Sigma Labs Inc., 2020). For example, the development of metal AM suffered from a lack of standardisation and a suitable certification methodology, such as quality control and assurance. The continuous development of AM attracted the attention of several standard-setting bodies (DE Editors, 2010) including the International Standard Organization (ISO), the American Society for Testing and Materials (ASTM), as well as technical institutions and industries. Refer to Appendix H for additional information on AM quality assurance.

Metal AM can currently manufacture end-user components that require superior mechanical properties with tight tolerance (Gibson & Khorasani, 2019; Jaster, 2019). Some of the advances made in metal AM include, but are not limited to, new materials (EOS, 2019; Nyrhilae et al., 2007), hybrid systems (Jiménez et al., 2021; Ortona et al., 2012; Tan et al., 2018), better material efficiency (S. Liu & Shin, 2019), simulation tools (Campbell & Bourell, 2020), heat sources and design optimisations (Ortona et al., 2012). The introduction of DirectMetal (bronze-based metal powder) of varying layer thickness and DirectSteel (steel based powder mixtures) in 1998 and 2003 supported metal AM (Nyrhilae et al., 2007; EOS, 2019). A study by Lind et al. (2003) showed that in 2001 it was possible to make functional metal parts with a smaller layer thickness of 20 μm. These studies opined that the benefits of improved surface quality, detailed resolution of the as-built parts and the added freedom outweighed the drawbacks of increased build time due to the use of thinner layers.

As-built part *refers to the state of parts made by an additive process before any post-processing, besides, if necessary, the removal from a build platform as well as the removal of support and/or unprocessed feedstock* (ISO/ASTM,2015). Earlier studies showed that DirectMetal 20^{TM} and DirectSteel H20^{TM} could be used to manufacture metal components having ultimate tensile strength (UTS) up to 400 MPa and 600 MPa by optimising process parameters values (Lind et al., 2003). Ultimate tensile strength can be described as the maximum stress a material can take before failure. Continuous material development introduced new metal powders such as titanium-based, cobalt-chrome-based, Nickel Alloy, stainless steel and aluminium powders for applications requiring high specific strength or hardness. There are currently only about 30 metal materials that are qualified for AM. Components built from such metal feedstock presently have mechanical properties equal to or superior to conventionally manufactured components in terms of UTS.

Earlier lasers were CO_2 based and the thermal energy of these lasers could not sufficiently melt metal. This was because, at the time, the CO_2 lasers had good enough beam quality and absorption for example coating and marking application. The absorption of CO_2 laser at room temperature was quite low for metals. Thus, they were predominately used to make plastics. This laser is still used with polymers that have adequate absorption for the wavelength of a CO_2 laser. The introduction of fibre laser system enhanced the technological shift from laser sintering systems to powder bed fusion (DMLS™ and SLM™) machines (EOS, 2019; H. Lee et al., 2017; Salminen, 2021). The shorter wavelength of fibre-based lasers enabled for full melting of metal powder in contrast to earlier sintering with CO_2 lasers. Full melting of metal powder in a layerwise manner enable fully dense metallic parts with improved mechanical properties to be produced. Continuous developments of metal-based AM such as DMLS™ machines (EOSINT M 270, EOSINT M 280) equipped with 200 W–400 W ytterbium fibre lasers with higher effective power and absorption in metals enabled higher build speeds (EOS, 2019). The commencement of high-power fibre lasers in the early 21st century is an important factor in the development of metal L-PBF (Samson & Dong, 2013; Salminen, 2021; EOS, 2019). Metal components currently can be manufactured with as high as 1 kW fibre laser in PBF and 6 kW fibre laser in DED machine systems (Pinkerton, 2016).

The introduction of affordable machines, simulation tools for component design optimisation and compatible metal powders also have supported the overall growth of AM (AMPOWER, 2019; EOS, 2019). Process automation, artificial intelligence (AI), high-powered and multiple lasers that enable faster production speeds and improved part properties have particularly supported the advancement of metal AM (Hällgren et al., 2016; Jaster, 2019; Khorasani et al., 2020; Sculpteo, 2020). Metal AM became an effective manufacturing method in the aerospace, automotive and medical sectors (Campbell & Bourell, 2020). Metal AM offered these industries new ways to create optimised metal components, energy-efficient metal components and shorter lead times compared to conventional processes (Hahn et al., 2014; Kok et al., 2018).

The AM subcategories that can manufacture metal components are binder jetting, directed energy deposition, powder bed fusion, material jetting and material extrusion (Simpson, 2019; Thomas-Seale et al., 2018). Metal AM can be divided into powder bed and nozzle feeder deposition technologies, as illustrated in Figure 2.5.

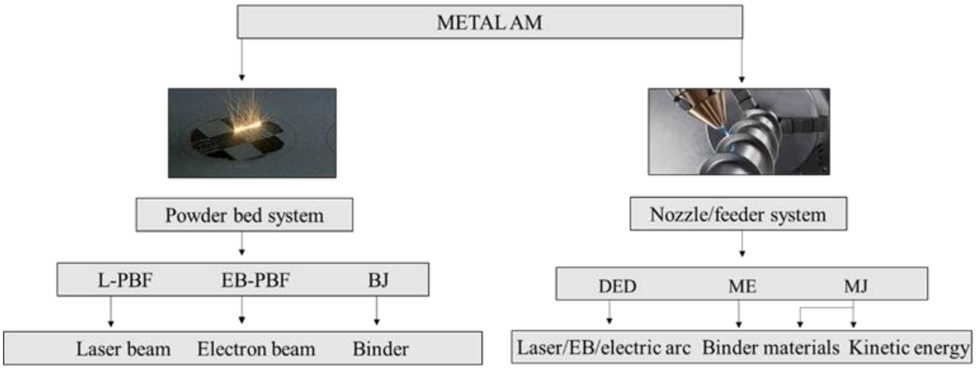


Figure 2.5: Representation of the different feasible subcategories of AM, feed system and mode of fusion for metal components with data from (Froes et al., 2019; Gonzalez-Gutierrez et al., 2019; Huckstepp, 2020; Khorasani et al., 2020; Saboori et al., 2017; Tofail et al., 2018; Varotsis, 2019; Zhang et al., 2018).

As Figure 2.5 shows, metal AM can be categorised into powder bed and feeder systems. The metal feedstock used in metal AM can be in the form of powder or wire and bonding can either be conducted with a heat source or a binding agent. Among the mentioned methods, directed energy deposition (DED) and powder bed fusion (PBF) is the most mature and widely preferred options for making metal components (DebRoy et al., 2018; S. Liu & Shin, 2019). This is because of their ability to produce fully dense parts (Jaster, 2019) with improved properties and higher flexibility to build complex designs (AMPOWER, 2019; Z. Y. Liu et al., 2018). DED is used to make components from either metal powders or wires (Z. Y. Liu et al., 2018). Binder jetting uses an injection mechanism to disperse binding material on the deposited material on the powder bed. It is therefore referred to as *powder bed and inkjet head 3D printing* (Zhang et al., 2018). Components manufactured with binder jetting and material extrusion are often fragile with limited mechanical properties and details (Jaster, 2019; Tofail et al., 2018). As-built components with binder jetting and material extrusion require mandatory second processing of debindering and sintering to obtain metal components with the required mechanical properties (Jaster, 2019; Gonzalez-Gutierrez et al., 2019; Simpson, 2019; Varotsis, 2019; Vock, 2019; Z. Y. Liu et al., 2018).

2.2.1 Laser powder bed fusion

Metal L-PBF in simple terms is a microscale laser welding (Ranjan et al., 2020) of metallic powder that creates a laser beam/powder interaction to form a melt pool. The thermal energy source in PBF is either a laser beam (LB) or an electron beam (EB) (Gibson et al., 2010). Laser-based powder bed fusion (L-PBF) refers to a form of PBF that uses the energy of a laser beam to fuse powdered material layer by layer on a powder bed in an inert gas-filled enclosed chamber. This terminology has changed over the years and is synonymous with terms such as *direct metal laser sintering* (DMLS™), *LaserCUSING*™, *electron beam melting* (EBM™), *selective laser melting* (SLM™) and LAM (Jägle et al., 2016; Jaster, 2019; Nyamekye et al., 2015).

None of the AM subcategories previously could effectively build functional metal components (AMPOWER, 2019; Salminen, 2021). No other thermal energy source except laser is presently capable of melting metal materials accurately enough. Laser-based techniques are effective AM processes as laser energy can solidify or cure materials in the air for high precision and high output using energy through a micro-scale focal point (Jiménez et al., 2019; H. Lee et al., 2017). The first commercial laser-based metal AM, EOSINT M 160, for DMLS was introduced in 1994 (EOS, 2019). L-PBF is presently able to manufacture fully dense metal components (Jiménez et al., 2021).

L-PBF is not design constrained and is often the preferred choice for manufacturing intricate metal components as the process can build any structure (Etteplan et al., 2019; Hereijgers et al., 2020; Singh et al., 2019) per the specifications of the machine size. Metal L-PBF can create a new range of components and improved new parts to replace old parts. L-PBF is currently the most widely used thermal energy equipped PBF for metal components (AMPOWER, 2019). L-PBF has proven to be a suitable choice for making lightweight, customised and consolidated designs (Autonomous Manufacturing Ltd., 2019; Najmon et al., 2019). This thesis concentrates on L-PBF as this method is widely used for making fully dense, high-resolution and reliable functional metal components (Huckstepp, 2019b; Jaster, 2019; Simpson, 2020). The lack of suitable material quality and the part precision to achieve the required mechanical and physical properties are still some of the obstacles to the adoption of AM for functional metal components (H. Lee et al., 2017; Tofail et al., 2018). It was hoped that the possibility of modifying the properties and application-specific materials for L-PBF would enhance technological growth (Lind et al., 2003; NRC, 2014). It is hoped that continuous technological development will identify a new way to enhance resolution in L-PBF to overcome the limitations of low surface integrity and accuracy (Jiménez et al., 2021).

Several previous studies have suggested that making functional components with L-PBF was limited by factors such as poor mechanical properties, poor surface quality, inadequate dimensional tolerance, high energy usage and high production costs (Baumers et al., 2016; Hahn et al., 2014; Khairallah et al., 2015; Mani et al., 2014; Ponche et al., 2014). Current metal L-PBF systems are equipped with laser systems with high power intensity and could potentially increase productivity. The current systems are also capable of making metal components with mechanical, thermal and fatigue performance comparable to conventionally fabricated parts (AMPOWER, 2019). Such advancements together with a new range of materials (Jiménez et al., 2021) widen the suitability of the L-PBF to replace conventional manufacturing methods in certain industrial applications (EOS, 2019). Components made with L-PBF sometimes outperform comparable conventionally manufactured components and surpass the predefined standardised values. Examples of this include better cooling efficiency with conformal cooling channels (Tan et al., 2020). Metal L-PBF sometimes surpass predefined standardised values of UTS and elongation in medical implant applications (AMPOWER, 2019). A schematic of the processing layout and working principle of L-PBF is shown in Figure 2.6.

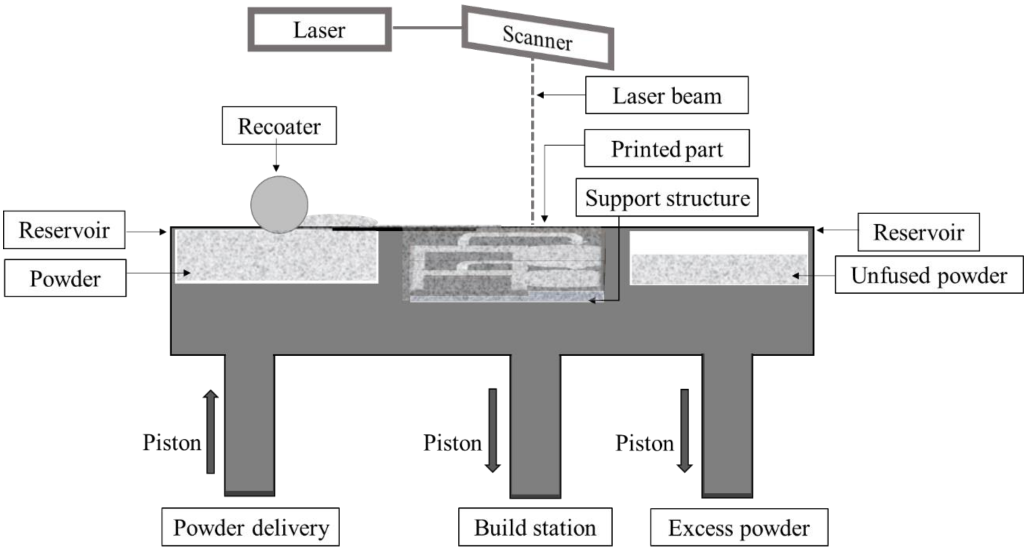


Figure 2.6: Representation of the L-PBF layout with data from (Foster et al., 2020; Frazier, 2014; Zhang et al., 2018).

Figure 2.6 shows the main components of an L-PBF system and the direction of movement. L-PBF begins with layering metal powder on the powder bed with the recoater once the powder reservoir piston has raised the powder for coating. The laser beam is transmitted via scanners onto the powder bed. The laser beam selectively melts the powder layer according to the sliced data. After melting is completed, the build platform is lowered and the powder reservoir is raised to provide a new layer of powder on the previously melted layer (Khairallah et al., 2015). The lowering of the build platform after each build layer also adjusts the tolerance (height) before spreading a new powder layer. This process is repeated intermittently with a laser beam fusing the powder particles in between each powder spread. The liquid molten pool of metal solidifies as cooling occurs behind the heat source, layer by layer. The melting of new layers can penetrate down to the previously solidified layer and this causes of joining of layers together. The remelting of sublayers is considered a challenge in metal processing; however, it is also an advantage because potential defects can disappear during remelting. The process is repeated layer by layer until a complete model has been printed (Gibson, 2021; Huckstepp, 2019b). Upon completing the part, the excess powder is collected in the excess powder excess reservoir. The excess powder can be reconditioned to remove any contaminants that might be caused by the uptake of gas and water molecules of the shielding gases (Daraban et al., 2019; S. Liu & Shin, 2019; Saunders, 2019). The reconditioned powder can be reused as a mixture with virgin powder for making components.

Metal L-PBF requires support structures to be manufactured along with the final components (Tofail et al., 2018). These support structures are necessary to ensure a successful build. Support structures are used for two purposes, first to anchor the component to the build plate, second to conduct heat away from the component, thereby preventing defects and part failure that could be caused by heat-induced distortion. Support structures act as heat-sink, thereby preventing thermal defects (Campbell & Bourell, 2020; Menu, 2018; Praet, 2017). The use of metal AM/L-PBF is inherently controlled by multiple parameters (Hansen, 2015; Ituarte et al., 2015; Piili et al., 2018) and this sometimes means it can be rather challenging to identify the optimal settings. There are many process parameters (see Appendix I) in L-PBF, around 130 (Hansen, 2015) to 200 (Fulga et al., 2017; Hansen, 2015) and this creates difficulties in process control. ISO/ASTM 52900-2015 defines process parameters as a *set of operating parameters and system settings used during a build cycle*. A build cycle is defined as a *single process cycle in which one or more components are built up in layers in the process chamber of the additive manufacturing system* (ISO/ASTM,2015). These include material characteristics and machine setting parameters. Conducting processing or design-related studies must be limited based on the expected property and affecting parameters of the final component. Such parameter selection and the aspects they control in the build process have been discussed in the literature (Khairallah et al., 2015; Laitinen et al., 2019; Oliveira et al., 2020; Saewe et al., 2019; Yadroitsev et al., 2015).

Powder handling refers to the features that a system requires to ensure successful and effective manufacturing. Powder spreading must not create an excessive shear force that affects the previously processed layers. The roller or recoating blade spreads the powder and smooths out the different layers of powder. The recoater also plays an important role in pressing the powder, thereby ensuring good packing properties of the parts (Foster et al., 2020). Powder handling system manufacturers must comply with these characteristics for the PBF process (Gibson et al., 2010). Different reservoir systems have been designed to ensure an adequate powder supply for the build process in powder bed technology. Powder reservoirs can be in the form of hoppers (overhead powder storage and delivery) or troughs (lateral storage tanks). The primary functioning components of a powder handling system are powder reservoir, powder transportation and spreading tool. In some systems, these three components (powder storage, transportation and spreading tool) are incorporated as one mechanism known as multi-functional powder handling systems. The functions of the different powder supply systems are as follows:

- **Powder reservoir:** There are two powder reservoirs, as can be seen from Figure 2.6. The start-up powder reservoir stores the input materials to ensure sufficient powder for the entire build process. This ensures uninterrupted manufacturing with continuous refilling of powder to the recoater. The second reservoir is used to store the unfused powders from the build plate

- **Powder transportation**: This implies the route used to get the required amount of powder from the reservoir to the build platform
- **Spreading tool**: Ensures thinning, smoothing and levelling of the deposited powder across the build platform

2.2.2 Advantages and limitations of L-PBF

There are enormous benefits of metal L-PBF that enabling efficiencies in different industry sectors (Betatype Ltd, 2020; Burkhalter, 2018; Fitnik, 2020; Herzog et al., 2016 Materialise, 2018; Monash University/Betatype, 2017). There are however several parameters such as material choice, data preparation and quality assurance to be considered in the adoption of any AM that goes beyond just the printable feature. Printable feature refers to features that can successfully be manufactured with AM. Defining the limits of printable features alone cannot support the argument of sustainability. There are also some shortcomings to this metal L-PBF that need careful planning and consideration to maximise the benefits. The production costs of components manufactured using metal L-PBF are often perceived to be high. This could be due to the tendency for the economic dimensions of the sustainability of L-PBF to be limited to the manufacturing phase. The advantages and limitations outlined in this thesis only pertain to metal AM/L-PBF to suit the scope of the thesis. The main advantages of L-PBF for making metal components include the following:

- **Design freedom:** Possibility of manufacturing lighter, strong and complex macro/micro-sized structures that would have been impossible to make using conventional methods. There is only a small limit to part structure as almost all geometries are achievable. Freedom to design complexity must be done per the process design rules for successful application
- **On-demand manufacturing:** L-PBF allows swift engineering/designing of functional and prototype parts with on-demand manufacturing to swiftly respond to market needs. Changes required in models are quickly and easily made by simply changing the parameters or shapes in the computer 3D models. New models can be designed and printed under very tight schedules as there are no tooling and machining constraints
- **Cost-effectiveness:** To a certain extent, L-PBF is cost-effective; there is no need to build a mould, which eliminates mould costs and allows swift design changes and an optimised component with enhanced functional value without adding to costs
- **Localised manufacturing:** There is the element of convenience as design and production can be conducted locally without any delays or extra work if properly planned. Detailed product designs can be electronically shared for local production, reducing transportation-related emissions that would other be generated when distributing the actual part
- **Raw material efficiency:** Metal L-PBF can manufacture components close to the final shape, thereby saving on raw material. Metal AM can effectively reduce

material wastage as only the regions of the powder bed that conform to the layers of the digital file are melted. This means that only the required metal powder is hit by a laser beam and melted during the build process

- **Conformal cooling channels:** L-PBF can make components with internal cooling channels. Incorporating a cooling path just below the surfaces of components such as mould tools and heat exchangers enable uniform and rapid cooling, which lowers the cycle time during their use phase
- **Customisation:** Possibility of creating customised components to meet specific objectives in applications such as aerospace and automobiles. This reduces labour intensity and the number of manufacturing methods often required to make customised components using conventional product design
- **Functionally graded materials:** Metal L-PBF allows for cost-effective manufacturing of new functionally graded components using multi-materials. The base material can be printed from inexpensive material and seamlessly coated with functional materials to satisfy functional requirements. The application of L-PBF for making metal components offers different benefits on the various stages of the value chain

Some several limitations/challenges hinder the acceptance of metal AM/L-PBF. Some of these include process and material-induced defects, component size limitations and an inherent large number of affecting processing parameters. Defects in components may include distortion, shrinkage porosity, delamination of layers, poor surface finish, thermal stresses (Chaplais, 2016; C. Chen et al., 2020; Zhai et al., 2014). Some of the inherent process limitations which are insufficient to satisfy all the stringent quality assurance requirements include low process speed, low part quality, high machine and feedstock cost (AMPOWER, 2019), to mention a few (Brockotter, 2021; Daraban et al., 2019; Dutta et al., 2019; Hinebaugh, 2018; Jimo et al., 2019; Menu, 2018; Sculpteo, 2020; Sealy et al., 2018; Yusuf et al., 2019). Some of the commonly discussed limitations of metal AM/L-PBF are summarised in Figure 2.7.

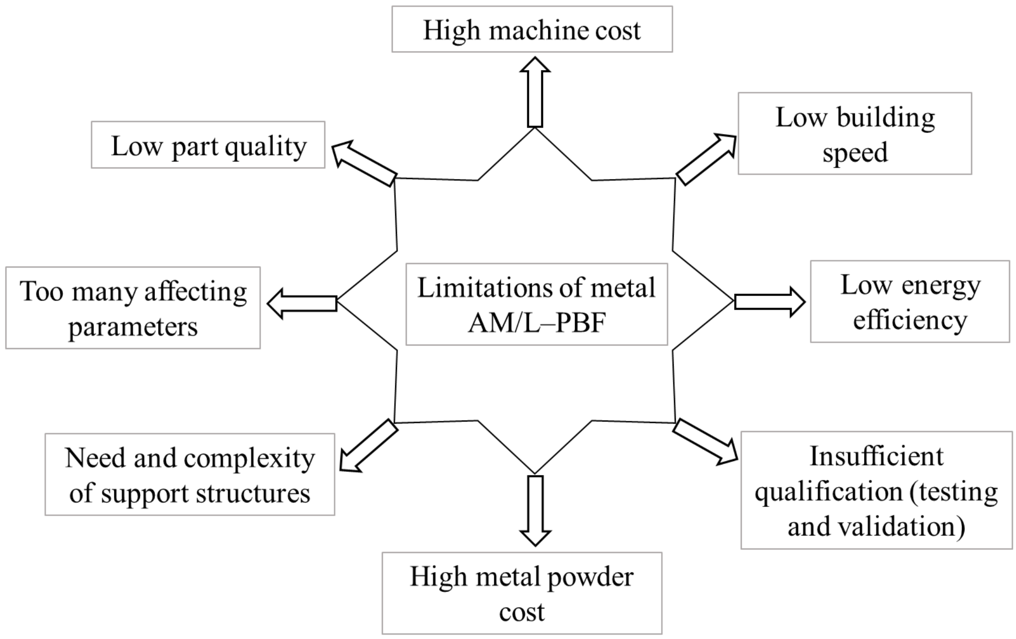


Figure 2.7: Limitations of the L-PBF industrial application.

Figure 2.7 shows the common limitations of L-PBF, particularly in metal applications. Metal powders are examples of materials that require excessive amounts of energy as input to the system during production. The L-PBF process may be limited in terms of energy efficiency. The high energy consumption in L-PBF is closely associated with the build process or auxiliary activities such as the preheating of powder. The parts produced may, in some cases do not have the expected tolerances and performance to fulfil inspection requirements. In some cases, poor mechanical performance can occur, as a result of, for example, porosity and the presence of thermally induced residual stresses and distortion of the metal component. The numerous affecting process parameters often require a separate set of optimisations. This can increase the difficulty of using L-PBF as there are no fit-for-all rules for the different processing phenomena. Poor part finish quality, prolonged build time, complexities of support structures and incomplete fusion are examples of limitations that can affect the cost and functional requirement.

Metal L-PBF consumes a high amount of energy during components manufacturing (Z. Y. Liu et al., 2018; Sharif Ullah et al., 2015). This, however, potentially can be reduced with simulation-driven designs and process parameters optimisation. These limitations are anticipated to be overcome with the increase in an academic and industrial effort directed towards design, materials and the building process in metal AM/L-PBF. The industrial uptake of L-PBF has led to the creation of more efficient machines, with high power and multiple lasers to increase build speed. New metal L-PBF systems are equipped with high lasers and better hardware solutions that are capable to omit some of the earlier existed limitations.

Research suggests that new developments in adaptive and innovative materials (Amelia, 2021), sensors and automation, closed-loop controlled powder handling, multi-layer concurrent printing (Aurora Labs Ltd 2019; Khorasani et al. 2020), multi-lasers (Khorasani et al., 2020), and uniform inert gas flow (Chen, et al., 2020) continue to emerge. These innovations are examples of potential solutions to overcome the current metal L-PBF limitations and to complement the current pace of machine developments. It is envisaged that the high cost of L-PBF will be reduced with better production efficiencies and will therefore contribute to increased productivity (Amelia, 2021). Digital thread of metal AM/L-PBF can create optimised designs to enhance energy consumption, materials usage, cost-efficiency and reduce waste which is otherwise impossible with conventional manufacturing.

2.2.3 Design and additive manufacturing

The design process is an approach that can be used to break down a large project into easily workable parts. The design of components is guided by two related processes (1) the logic of problem-solving in design and (2) the formation of concepts that support customer choice (Clark, 1985). The former refers to a design hierarchy that breaks down the problem into parts in order to establish an order of significance. The latter refers to the customer concepts used to understand the product and the development of criteria to be used in the evaluation. The design of products can be described as an iterative process that connects different hierarchical aspects in order to select the best solution to a problem via optimisation. The iteration of potential solutions is analysed based on experience, intuition or mathematical analysis during a component design process in order to select the best solution to the design problem (Arora, 2017). According to Arora (2017), a best system is characterised by enhanced cost-effectiveness, efficiency, reliability and durability. According to Clark (1985), the final design structure encompasses sequences of design decisions that also determine the pattern of change in a product or process. Arora (2017; Clark (1985) identified components of the design as a procedure of process analysis, of identifying major systems, the components of the structure and sub-systems.

Characterising these aspects in different ways is necessary as this can demonstrate the interrelations, functional areas or phases that are significant. A particular functional parameter can dominate and drive the decisions and actions as an apex (core) in the design process that affects the other elements of an individual design sphere. The relationship between the functionality and the significant aspects of the design process is also necessary to identify their effects on the final components. The choices made in one process stage can determine the choices in other stages (Clark, 1985). Such an approach can simplify the identification of the stages necessary in managing a project.

Designing components can be visualised as interrelated processes that connect the system definition process, component design process, manufacturing planning and quality assurance process. When narrowed down to metal AM/L-PBF, all these elements involve distinct activities for fulfilling the expected design objectives as Figure 2.8 shows.

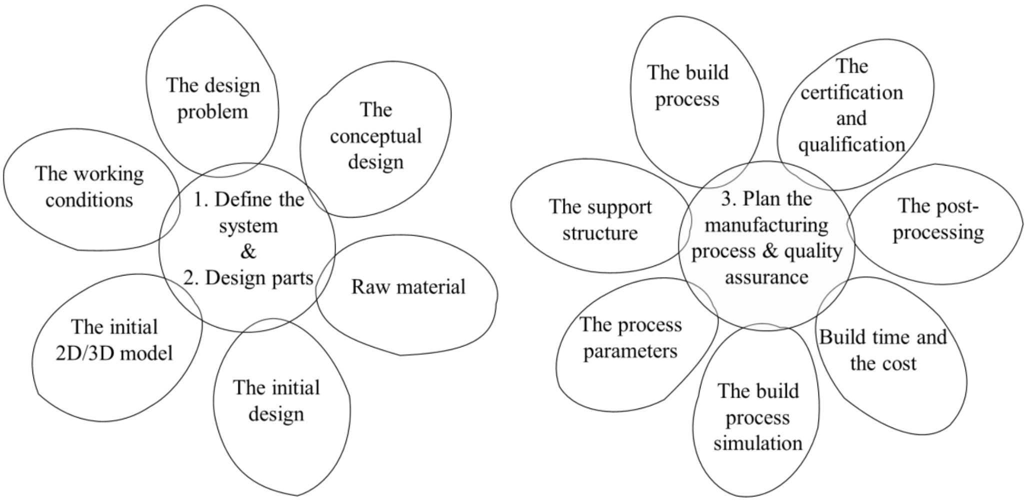


Figure 2.8: Representation of a schematic and stepwise model for design in metal AM/L-PBF.

Figure 2.8 shows that a cohesive design process for (1) system definition, (2) components designing and (3) planning of the manufacturing systems for achieving maximum benefits. The defined system process investigates the objectives of a component and considers the context in which the component will function. The system definition encompasses aspects such as component selection concerning functional requirements, functional conditions in which the component will be used, relationship to other components as an element of a larger component.

The design part process involves the actual modelling of a component structure based on various expected features in relation to other elements. The use of sketches to document ideas can help keep track of concepts throughout the detailed design phase to make the CAD designs. The optimisation and validation of feasible designs can be achieved with simulations by defining the applied loads, forces, constraints and other factors.

The plan manufacturing process identifies and plans the various manufacturing steps and QA. The manufacturing steps include planning the AM/L-PBF and post-processing. For example, optimised process parameter values are selected and post-processing is planned. Part placement or packing takes place when part orientation has been decided for optimal support selection, reduced manufacturing time and improved productivity (Leirmo & Martinsen, 2019; Thompson et al., 2016). Optimising these aspects can enhance the designing of cost-effective, material-effective and reliable components that are free of undesirable voids of defects. For instance, the careful planning of part placement and optimal building parameter values selection can positively or negatively influence the economic and environmental aspects throughout the LC (Mele & Campana, 2020).

2.3 Sustainable additive manufacturing

Designing components that can enhance effective resource consumption, decrease costs, reduce transport emissions and other environmental impacts positively contributes to achieving some of the targets of the SDGs 7, 8, 9, 12 and 13. AM meets some of the targets of the SDGs through localised manufacturing, increased demand for research, extended product life and resource efficiency. This includes a substantial reduction in energy usage and operational costs during the use phase. AM could feasibly enhance material circularity, reuse, repair and the re-manufacturing of components after EOL. AM has an efficient raw material utilisation of around 65–99%, depending on the subcategory used (Croft Additive Manufacturing, 2020; Inside Additive Manufacturing, 2017; Ma et al., 2017; Serres et al., 2011; Xiong et al., 2008).

L-PBF is an example of an AM method that offers the possibility of achieving such objectives with metals. AM has the advantage of manufacturing optimised and intricate designs compared to conventional manufacturing methods (See Appendix J). L-PBF makes a very significant contribution to increased efficiencies and decreased inefficiencies in manufacturing metal components (Gutowski et al., 2017). For example, a virtually 100% material utilisation rate with extended component life can be achieved (Gutowski et al., 2017). This could potentially enable almost 99% of material utilisation (Nyamekye et al., 2017) with proper planning of support structures and optimised processing parameter values. Most of the input and powder removed from the build chamber and finished components can be reused for new builds (Saunders, 2019). Excess powder during the manufacturing phase can be reconditioned for reuse for new builds (Daraban et al., 2019; Saunders, 2019). A negligible proportion of the material is removed as waste in the form of chips or support structures during post-processing. Metal powder is reusable many times for new builds in L-PBF. The recycled powder may lose the prerequisite morphology and integrity (Jiménez et al., 2021). Reconditioning of the physical and chemical properties is often required to restore powder properties (Saunders, 2019).

Despite these advantages, not there is little known about the material efficiency on the raw material acquisition level AM can transform how goods and services are processed and delivered (Baumers et al., 2017; Daraban et al., 2019; Laverne et al., 2015; Tofail et al., 2018). Companies are beginning to employ AM as a tool for achieving objectives such as energy efficiencies, raw material efficiency, shortened supply chains,-swift time to market, LC costs savings, as well as emission-free production (Baumers et al., 2017; Godina et al., 2020; Savolainen & Collan, 2020). AM is also revolutionising how companies operate (Jiménez et al., 2019; Mojtaba khorram niaki, 2015; Savolainen & Collan, 2020) by moving from mass production to mass customisation, localised, flexible and on-demand manufacturing (Baumers et al., 2017; Croft Additive Manufacturing, 2020; Market and Market, 2020; Saxena et al., 2020).

Metal L-PBF allows the successive delivery of energy to specified areas in a layer-wise manner. Metal components manufactured with L-PBF offer ways of reducing indirect emissions and energy consumption in the production of raw material through reduced material waste. There are potentials to improve the design system, use-phase efficiencies (through extended life, reduced weight, fuel consumption and emissions), localised manufacturing, technological flexibility (Daraban et al., 2019; Godina et al., 2020) and EOL. These benefits are classified according to the environmental, economic and social aspects of sustainability. The specific advantages of the manufacturing phase of L-PBF are summarised in Table 2.1.

Table 2.1: Benefits of L-PBF that support sustainable manufacturing.

Environmental	Economic	Social	References
• Automation • Shorter processing and lead time • Less wasted materials • Cleaner energy with a laser	• Reduced manufacturing costs and storage • Lower tooling costs • Shorter lead time, thereby cost reduction • Fewer spare parts • Multi-materials to reduce cost	• Job creation via localised manufacturing • Joint national and international cooperation • Online and offline co-creation with customers • Accessible to all • Customisation	(Betatype Ltd, 2020; Caprio et al., 2020; Delva Oy, 2020; Jiménez et al., 2019; Najmon et al., 2019; Putra et al., 2020; Rayna et al., 2015; Tofail et al., 2018; Zadpoor & Malda, 2017)

The benefits of AM for sustainability and the CE extend beyond the manufacturing phase to the use and EOL phases. Huang et al. (2016) Sauerwein et al. (2019), have shown that AM increases the service life of products which is an aspect of the CE. Making durable components, reducing the quantity of raw material, created waste and emissions from manufacturing new components reduces CF. Figure 2.9 illustrate aspects of industrial operations in which metal L-PBF offers sustainability benefits.

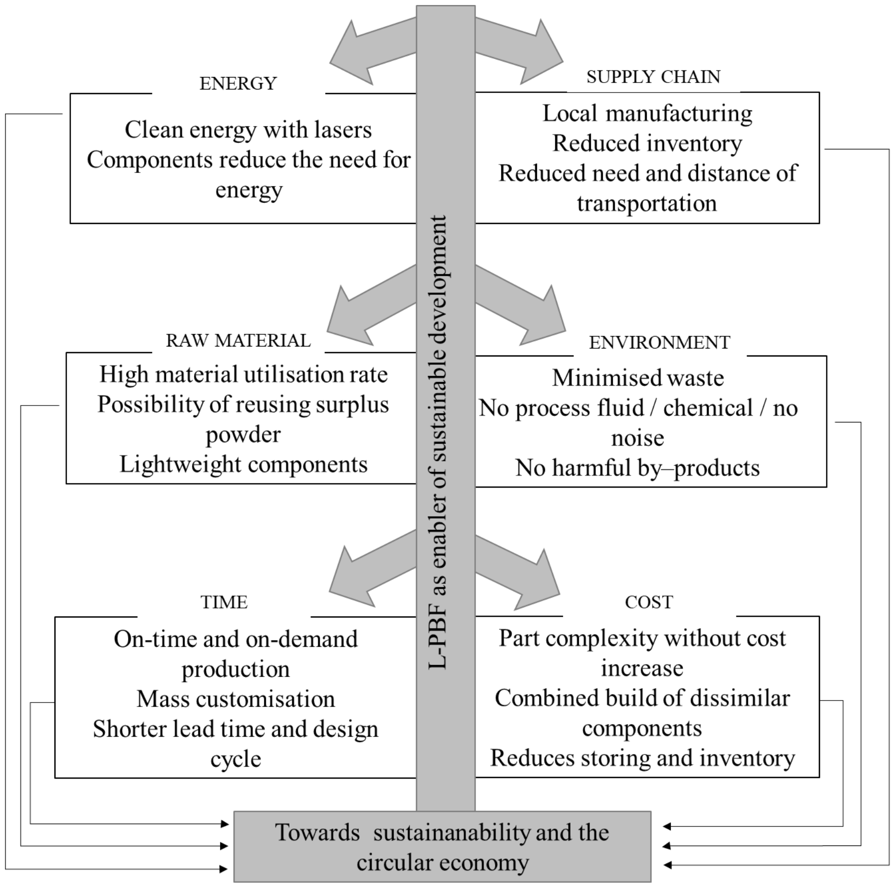


Figure 2.9: Aspects of metal L-PBF and the enablers to sustainable manufacturing.

As Figure 2.9 shows, L-PBF offers multiple benefits: enhanced performance, increased productivity and cost-effectiveness. It is anticipated that metal chips/scrap removed as waste can mechanically be ground and reused for example DED as input raw material (Salminen, 2015). Further study is required to ascertain this potential. In comparison, metal AM (for example, L-PBF) can be used to manufacture components with enhanced properties, functionality, durability and cost-effectiveness, which is not achievable via conventional manufacturing (for example, moulding, machining).

3 Strategies to enhance the growth of metal L-PBF

The activities of industrial engineering are, in practice, both business and engineering centred (Arora, 2017). A component design must be considered in terms of whether using a specific manufacturing method will offer benefits such as improved reliability, functionality, durability, aesthetic, customisation, resource efficiency and cost efficiency, depending on the use case. The optimal design is often required to satisfy different functionality. Ensuring that the component will offer added value is one of the main reasons why aspects of business strategies must be considered. This will require well-informed decisions to be made regarding which comparable method (e.g., metal L-PBF or CNC machining) will be sustainably valuable. Value analyses of companies may emphasise efficiency, innovation and cost (The Royal Academy of Engineering, 2012).

The adoption of metal AM/L-PBF to enable sustainable manufacturing cannot advance solely on the benefits that the method offers. The readiness to implement at the management level and supportive adoption strategies are equally important to ensure that this novel method offers the anticipated advantages. There is a need to gain a better understanding of how the method can be used to achieve integrated environmental and economic benefits. This will support decision-making in line with the sustainable development strategy of (Brundtland, 1987). There is a need to understand the cost structure and related factors that can influence sustainable economic choices. Value chain analysis and SWOT models of metal AM before adoption can also help identify the best opportunities that can be used to improve the value and create long-term economic sustainability.

3.1 Costs of metal AM

The manufacturing costs for metal AM differ for the different subcategories listed in Figure 3.1. There is a common notion that complexity is for free in AM. Manufacturing complex components with conventional manufacturing methods are often labour intensive, requires more tooling and manufacturing steps, whereas AM can maintain a constant cost structure while increasing complexity (Fraunhofer, 2016). Comparisons of the production costs for conventional manufacturing (CM) and AM based on complexity and batch size are shown in Figure 3.1.

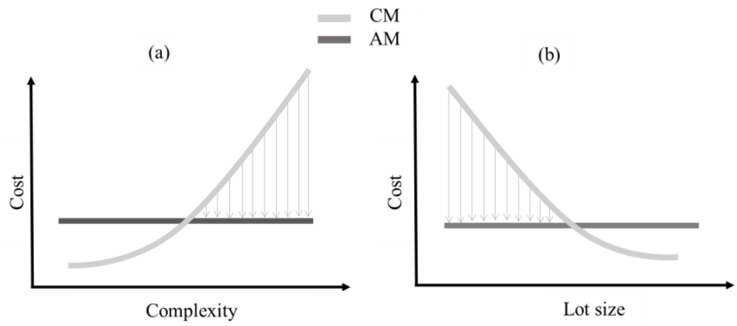


Figure 3.1: Illustration of influence of (a) complexity and (b) lot size on costs of CM and AM. Adapted (Fraunhofer, 2016).

As can be seen from Figure 3.1, the cost trend of manufacturing with AM remains constant as the complexity increases The striped area from the meeting point of CM and AM in Figure 3.1a shows when AM becomes the most effective option for reducing the cost of making complex designs. This implies that component designs that are difficult with a conventional design system could be initially considered for AM. Conventional manufacturing could be a more cost-effective option for making components that require a minimal level of intricacy, or vice versa. Practically, however, the more complex a component design is, the more complex the support structures will be. Increasing the complexity of the support structures can increase manual labour, time and cost to remove them. The trend of AM costs may increase after the stripped area due to support structure complexity. Induced costs. Optimal designs with easy to remove support structures is the ideal way to keep AM cost constant. Figure 3.1b shows the influence of the number of produced components on cost. AM allows series production at a low cost, as can be seen. Increasing the number of components can increase the production costs of AM. The cost inefficiency may be attributed to part size and lot size limitations. The striped area at the intersecting point of Figure 3.1b indicates when switching to CM will be cost-effective. Utilising such an analysis will allow companies to compare competing methods and identify the most economically viable option. Nearly all high technology, including AM, incurs losses during the early stages. Costly specialist facilities and complex market entry are often required before investments can be turned into profits, regardless of know-how (OECD, 2017). The comparison of costs in manufacturing is most effective only after the maturity stage (Schwarzer, 2013).

The main components of L-PBF costs are design costs, machine costs, material costs and post-processing costs (Jiménez et al., 2019; Simpson, 2020). Other contributory elements could impact the cost of L-PBF that often remain hidden until they emerge. Considering these costs can be useful for overcoming any surprises. Examples of such costs are qualification testing, overhead costs such as support staff, monitoring, consumable costs (for example, gases), build plate removal, lighting and cleaning (Ray, 2006). A comparison of the part resolution, part size and cost structure will differ, based on the type of AM used. A specific method can be applied to achieve part size within a certain range, as shown in Figure 3.2.

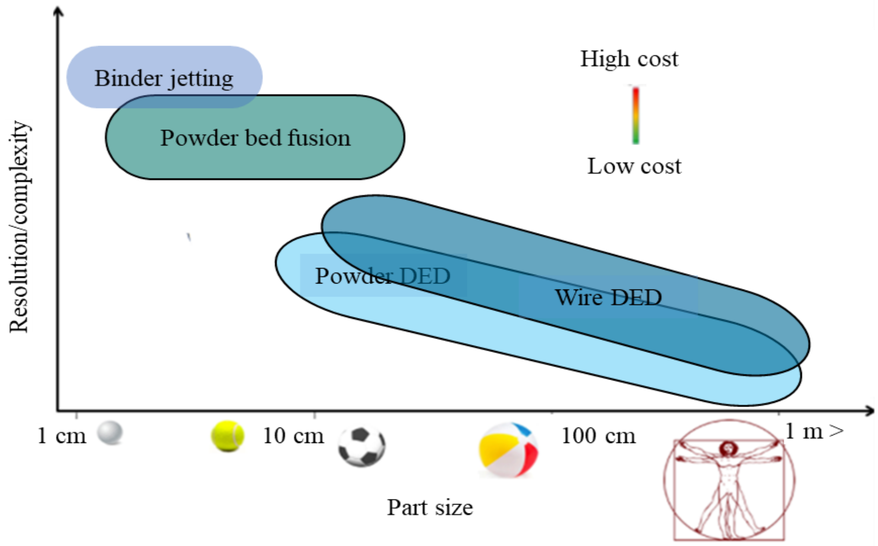


Figure 3.2: Comparison of different metal AM based on the degree of resolution/complexity and manufacturable part size. Modified from (Huckstepp, 2019a).

Figure 3.2 shows that different AM methods can be used to manufacture components based on the desired resolution, complexity and size of the component. The quality of the component, part size, flexibility to manufacture intricate designs and costs can differ with each of the AM subcategories. The different subcategories can make components of varying complexities, resolutions and sizes. Currently, PBF and binder jetting systems can build components with part size variation from 1 cm to 10 cm. DED is capable of making components larger than 1 m with both powder and wire-based DED, the part quality may differ depending on whether a metal wire or powder is used.

L-PBF offers advantages such as high resolution and flexible options for controlling costs by increasing the utilisation rate of the build platform (Salmi et al., 2016). The more efficiently the build platform space is used, the better the production cost per unit. An estimation of costs based on build platform utilisation has been presented in this thesis. However, it does not include a practical evaluation of costs. The energy used by process auxiliaries, for example, spreading powder material and cooling the laser, remains the same regardless of the utilisation. A batch comprising a smaller number of components will consume the same amount of energy (kWh) for these, assuming the same L-PBF system, time and power is consumed. Energy is defined as the product of the power consumed (kW) in making a component within a given time frame (h).

The costs benefits offered by metal L-PBF must consider the overall cost (Williams et al., 2020) of the components including design, manufacture, use and EOL, as certain costs incurred at one stage can offset other costs in another phase. Metal L-PBF is inherently expensive as a result of high investment and operating costs than comparable methods (Williams et al., 2020). Investment costs could relate to the metal L-PBF machine and material costs. The manufacturing phase of L-PBF requires the careful selection of part orientation as this can affect the complexity and need for support structures. Increasing support structures could increase energy and material consumption. The need for support structures potentially can also be reduced through proper selection of process parameter values and use of recommended geometry limitations according to the DfAM guidelines.

The ability to make defect-free components will reduce both resource and time wastage, thereby helping to maintain cost-effectiveness. Reducing manufacturing time, the need for support structures and the rate of failed components must be the focus of the design for improved cost and resource efficiency. Such cost reductions are attainable with simulations and using the DfAM guidelines. In a study, Simpson (2020) showed that light-weighting, increasing process speed and lower material costs were some of the driving elements to decreasing overall production costs. The use of DfAM guidelines for reducing weight has been shown to be the main contributor to achieving cost efficiency. The study showed based on the study data that, approximately 40% the weight reduction and about 54% cost reduction using DFAM (Simpson, 2020). This reduction is only based on this study and does not represent a generally benefit as different machine systems may have different cost drivers. Components of sustainable value creation can be enhanced in AM because of the availability of digital tools. These tools allow virtual designing, testing and manufacturing of components in order to select the most optimised designs and process parameter values (Daraban et al., 2019; Jiménez et al., 2019).

3.2 Business models

AM offers design freedom opportunities and speed to market with a seamless digital value chain capable of eliminating a physical inventory. The digitalised value chain of AM extends beyond the physical premises of manufacturing companies. The new form of digital inventory and warehousing, digital design and manufacturing support all-LC phases of products. The digital AM thread offers opportunities to innovate from the product design, production, use and EOL stage. The digital value chain of AM reduces the workload and costs that companies bear in their efforts to promptly respond to the needs of production or customers (Jimo et al., 2019). Some conventional manufacturing methods also use a digital supply chain when creating CAD models and the corresponding machining coding that can be modified or used directly to manufacture components.

3.2.1 Value chain

Value chain refers to the step-by-step internal activities in which companies engage to transform services, ideas and materials into physical output (Ovidijus, 2013). Companies may either perform all aspects of the primary activities of the value chain, from product design to finished part or use the facilities of service providers for reasons such as cost reduction and low volume production (Jimo et al., 2019). Service providers in this thesis may refer to third party companies that offer design, manufacturing and consultation such as business advice on the strategic use of AM, but which do not engage in direct sales of components to end-users.

Value chain analysis (VCA) is a process that helps companies identify primary and supporting activities and understand potential sources of competitive advantage (Fisher et al., 2020; Ovidijus, 2013, The Royal Academy, 2012). Corporate social responsibility (CSR) creates values from the social dimension for companies to succeed and not as a threat that will increase their operational costs. A company can use the aspects of sustainability to achieve CSR goals for the planet, people and profit (Youmatter, 2020). The needs of customers and society can trigger innovation, for example, creating tailor-made material of a specific quality to satisfy a specified function (Tofail et al., 2018) and enhancing sustainability practices to enhance the reputations of the company (N. Lee & Lee, 2019).

VCA may be used as a tool to enhance the differentiation advantage or cost advantage (Ovidijus, 2013). Differentiation advantage is achieved by creating superior products and adding more features to satisfy varying customer needs. Such an approach may increase costs but offers better durability and functionality of components during the use phase. The approach to VCA is based on three steps: (1) identify activities that create value for the customer, (2) evaluate the differentiation strategies that most facilitate the improvement of customer value and (3) identify the most sustainable differentiation options (Agada, 2020; N. Lee & Lee, 2019; Mingione & Abratt, 2020). A cost advantage aims to enhance resource efficiency by delivering the most cost-effective components. This approach tries to understand the sources of cost advantage or disadvantage and the factors that drive these costs. Ovidijus, (2013) identifies five steps in the cost advantage: (1) identify the primary and support activities such as inbound material, outbound goods, after-sales services in delivering customer value, (2) establish the relative importance of each activity to the overall costs. Inefficient activities can be identified and addressed in a benchmarking scenario, (3) identify cost drivers for each activity to understand their driving factors and take the necessary measures to reduce them, (4) identify links between activities to understand and identify effective ways of reducing the cost and (5) identify opportunities for reducing costs in order to understand and plan ways of improving the most influential activities and cost drivers.

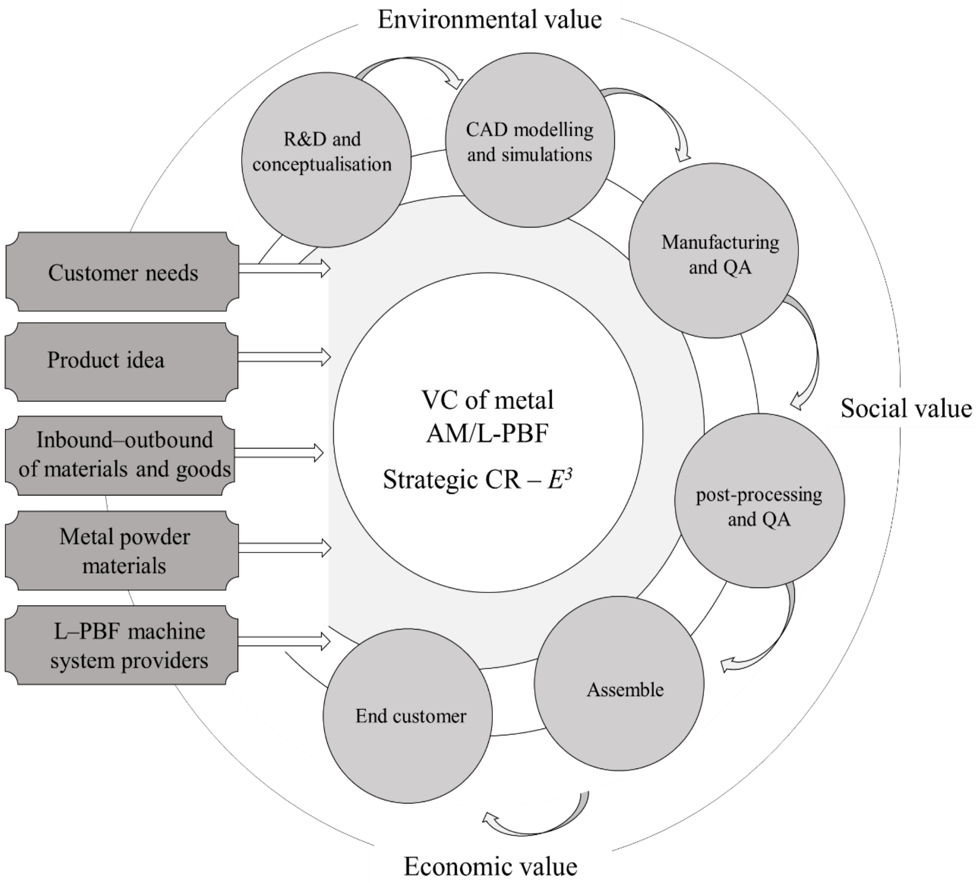


Figure 3.3: Representation of AM value chain in manufacturing.

Figure 3.3 shows the value chain in L-PBF. The machine and powder materials form part of the value chain. AM allows co-creation between the system, powder manufacturers and their customers to meet the specific needs and requirements of strategic CSR or sustainability. The essential reason for using a new process is to enhance efficiencies, productivity, quality, seamless data chains, security and to reduce costs. The digital value chain is an example of how AM is positioned as an enabler of sustainable value manufacturing in the current industrial revolution, industry 4.0 (Tofail et al., 2018). The digital value chain enables faster product development and on-site production for a simplified supply chain. A holistic approach that incorporates the entire value chain (see Figure 3.3) in consideration of strategic cooperate sustainability could lead to better sustainable competitiveness. A holistic evaluation refers to analysing the required properties and effectiveness of components throughout their cycle life using a simulation tool, LCC and LCA models.

3.2.2 SWOT analysis

SWOT is a technique for analysing specific aspects of strengths, weaknesses, opportunities and threats (Narsimlu et al., 2017) and can be conducted along the value chain to identify internal and external competing factors. The technique can reduce the likelihood of a company failing, by understanding what is lacking and eliminating unexpected risks. A SWOT analysis allows companies to make the most use of their portfolio. The SWOT model can be used to assess the current position of a company before deciding to undertake a new strategy (Scandura & Gower, 2020). It can serve as a situation analysis tool based on internal (strengths and weaknesses) and external (opportunities and threats) competition conditions, as Figure 3.4 illustrates.

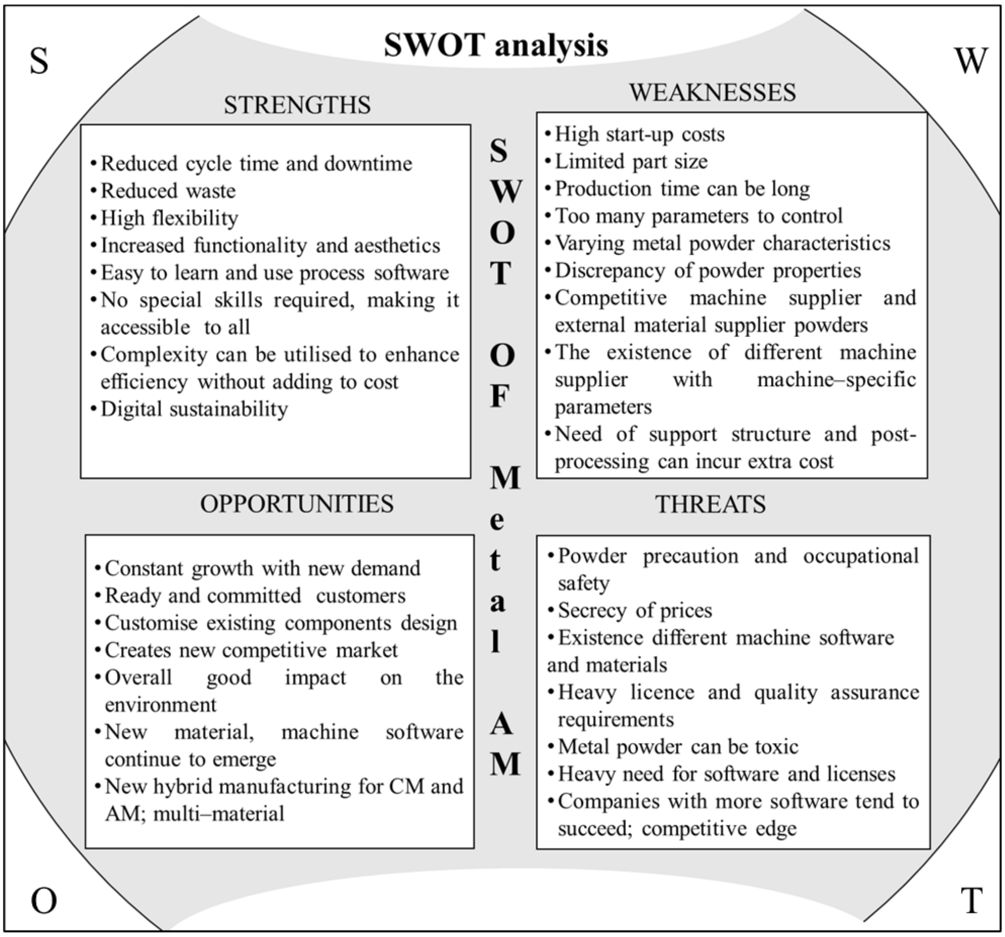


Figure 3.4: Applicability of SWOT analysis as a strategic approach to the adoption of metal AM.

A SWOT analysis, as in Figure 3.4, can give conclusive indicators for companies to excel both present and future through listing the elements of the four segments. A SWOT analysis is very company dependent and relies on the position of the companies in the value chain. Strengths and weaknesses must be considered internally and opportunities and threats externally from a competitive perspective. Strengths and weaknesses refer to the positive and negative traits that respectively give or prevent a company from having a competitive edge. Opportunities are feasible factors that can help companies succeed. Threats are the likely harmful factors that are often beyond the control of companies (Mindtools, 2020; Scandura & Gower, 2020). One threat in powder-based AM is the toxicity of metal powder. ASTM F3049-14 does address any safety and health concerns. Precaution must be taken to avoid the risk of inhaling the fine metal powder or to the skin. Protective clothes and safety glasses must be taken to ensure no external or internal body is exposed to powder.

3.3 Design for additive manufacturing

DfAM is an approach to using a set of design rules to design components and to select optimised designs and process parameters, for example, to help exploit the full benefits of AM (Laverne et al., 2015; Thompson et al., 2016). DfAM offers the potential for optimising component design based on the intended function (Peng et al., 2020) and to reduce the need and cost of both pre and post-processing (Campbell & Bourell, 2020; Simpson, 2020). DfAM is a revolutionised methodology for designing optimised components. DfAM changes the approach to product design to include optimised factors such as material choice, process parameter selection, geometric appearance, simulations, post-processing and so on. DfAM takes into consideration the design requirements of the final product (Ponche et al., 2014), manufacturing requirements (Pradel et al., 2018) and requirements for functionality and material choice (Alghamdy et al., 2019). ISO/ASTM 52911-1:2019 is the standardised guidelines of feature specifications and detailed design recommendations for metal L-PBF (ISO/ASTM, 2019). ASTM F3049-14 (ASTM, 2014) is an adopted standard guide for characterising the properties of metal powders used for AM. The standard harmonizes the quality and uniformity of feedstock properties. The I standard aims to promote confidence in powder selection and to ensure the reliability of manufactured metal components.

Product planning at the early stage of design following the DfAM rules offers a new way of rethinking geometry design, material selection and process selection (Alghamdy et al., 2019; Gibson & Khorasani, 2019) in AM compared to conventional product design. Efforts must be made to ensure the suitable process parameters and solutions are selected to reduce defects and to achieve the design intents and minimise environmental and economic impacts. The operating temperatures and conditions, for example, the presence of acids, potential process forces must all be considered before the material selection and before creating the component design. Optimisation of laser power values will ensure that the right temperature is selected to achieve sufficient melting for the required penetration and to reduce for example spattering. Modification of the laser shape (pulse shaping) for gradual melting can also stabilise melt pools. This can reduce the formation of spatters (Molitch-Hou, M. 2017) that affect the quality and mechanical properties of the final parts (Gutowski et al., 2017; Piili et al., 2018). Spatters are formed when tiny particles of liquid metal are ejected from the melt pool into adjacent areas during the movement of the laser beam (Molitch-Hou, M. 2017). This approach of optimised product design is unique to AM/L-PBF.

Component design, process parameters and constraints need proper utilisation to achieve successful manufacturing results with AM (Culleton et al., 2017; Laverne et al., 2015; Rosen, 2007; Thompson et al., 2016). The use of organic curves over right-angle joints, for example, ensures safer manufacturing and reduces the need for support structures. The use of a sufficiently flat surface for the initial layers attached to the build plate ensures proper anchoring of the component to the build platform (Stone & Cooper, 2017). The right product design for AM is not merely about selecting the right design; it is also about selecting the right process and materials. The right AM process must be selected to avoid errors and defects to achieve reliable and quality components. This enables the creation of a perfect trifecta of part complexity, simplified manufacturing and improved performance to satisfy cost, inspection and performance requirements. The input feedstock characteristics also have the potential to overcome some of the limitations such as anisotropic microstructure and slowed build speed. The selection of the feedstock and the process parameters must guarantee that significant problems are improved in order to achieve the required mechanical properties and production efficiency (Kok et al., 2018)of the final components. The processing must be controlled to reduce the tendency of errors and defects. The feedstock must fulfil the process-specific criteria. A feedstock of good fluidity, high distribution density, low moisture absorption and high chemical stability can form stable and regular properties for satisfactory process reliability and productivity (Amelia, 2021).

The heat conductivity of a material is its ability to conduct or transfer heat (Burger et al., 2016; Merriam Webster, 2014). The high heat input in metal L-PBF using laser beams must have an easy way of escaping after melting the layers to avoid heat accumulation. Materials with poor heat conduction accumulate heat, thereby tending to cause thermal distortions and cracks. Stainless Steel 316L, for example, is a widely used material for producing metal L-PBF components. This material is suggested to pose the problem of poor heat conductivity, which can cause a delay in cooling. This, in turn, can decrease the processing speed and even result in defects. The product design must select materials that have similar qualities, which can fulfil the same functional requirements at less cost. Inconel is an example of a substitutional material that offers equally similar mechanical properties to stainless steel with better heat conductivity, processing speed and easy printability. The ease of buildability for one than the other may be due to discrepancies in utilised machine system, process parameter value and other affecting factors. As such buildability cannot be generalised to be better with one material than the other.

Metal L-PBF is characterised by localised temperature gradients due to the rapid melting and solidifying (Fayazfar et al., 2018; Hooper, 2018; Jägle et al., 2016; Thijs et al., 2013) in the range of 10^4–10^6 K/s (Hooper, 2018; Jägle et al., 2016). The high cooling rates make the process ideal for achieving features such as a fine microstructure and high strength components (AMPOWER, 2019; Fayazfar et al., 2018; Thampy et al., 2020; X. Zhao et al., 2008). The repetitive thermal cycles (Fayazfar et al., 2018; Li et al., 2018) in metal L-PBF can result in undesirable grain growth along the direction of build and can act as an initiation point of cracking (Kruth et al., 2004; Liverani et al., 2017; Thampy et al., 2020). This can increase the brittleness and residual stress in certain materials, which can affect quality, due to their sensitivity to cracking (AMPOWER, 2019; Kempen et al., 2014). AM requires a synchronised approach to optimised product design and this is achievable with the proper use of digital tools.

3.3.1 Design optimisation

Design optimisation can integrate certain kinds of physical behaviour modelling into components to synthesise optimised structures according to functionality and requirements (C. Chen et al., 2020; Etteplan, 2020; Ramsaier et al., 2018; Stetter, 2020). Optimised design can improve the longevity and performance of L-PBF components. Structures such as lattices, scaffolds, hollowed walls and conformal ribbing may either be incorporated into the entire architecture of the component or as internal macrostructures for behavioural depictions of technical systems. DfAM entails the designing of components that takes into consideration the part size, geometries and material composition according to the constraints and capabilities of AM. There are numerous ways in which the geometry design of components can be optimised. This thesis highlights two commonly publicised optimisation methods that have supported the use of metal AM/L-PBF in even the most rigorous industrial sectors. These are (1) topology and (2) lattice optimisation, which create designs to meet goals such as lightweight, material volume reduction, reduced production throughput time, reduced cost, improved strength-to-weight ratio, better stability, stiffness and desirable thermal behaviour (Ashby, 2006; NRC, 2014; ProtoCAM, 2018; Shamvedi et al., 2018). These optimisation methods can reduce the need for raw material through the creation of lightweight components while maintaining functionality.

Topology optimisation is a mathematical method that uses finite element models to optimise the design by effectively distributing the available materials in the limitation of the design space (Rosinha et al., 2015; Zhu et al., 2021). This method creates optimised designs in fulfilment to set boundaries, applied load and other defined goals. Topology optimisation identifies and removes sections of design space that do not form essential aspects of a part or contribute to the functionality of components (3DScienceValley, 2018). Topology optimisation requires the reserving of sections that are necessary for the proper functioning of components as an individual or performing units of a larger assembly. For example, holes for attachment to another component and other parts that must remain untouched are defined as ‘frozen’ in functional generative software. These sections remain intact during the iteration to create optimised designs, (see Appendix K1), thereby maintaining dimensional stability and functionality.

A lattice optimised design can comprise multiple similar or dissimilar cells beams to fill up a design space. The porous-like structure of lattice designs enhances stiffness, strong load-bearing and reduces weight. The advantages of turning solid structures into foam-like bodies (see Appendix K2) can result in better raw material consumption rate, energy efficiencies, improved functionality, better stability, desirable thermal behaviour and cost reductions (Ashby, 2006).

The orientation and types of lattices can be designed to offer varying properties within a component to satisfy requirements, thereby creating hierarchical porosity. Sierra-Salazar et al. (2019) define hierarchical porosity as *the combination of pores of different sizes (micropores: smaller than 2.0* nm*; mesopores: between 2.0 and 50.0* nm*; and macropores: larger than 50.0* nm*)*. Gladysz & Chawla (2014) refer to such hierarchical porosity as *voids*. Optimising design geometries via the creation of hierarchical porosity can save part weight, raw material consumption, manufacturing time and costs. requirements.

Topology and lattice optimisation can be used to improve fuel and energy efficiency, strength-to-weight ratio and biocompatibility in fields that require such functionality (Campbell & Bourell, 2020). Different optimisation methods may be used solely or as a combination (see Figure 3.5) of more than one feature to target weight reduction, better stability and desirable thermal behaviour (Altair, 2018).

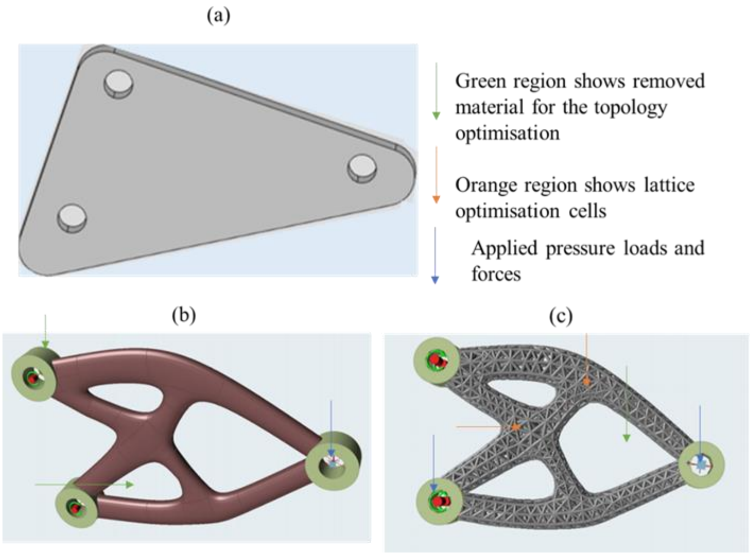


Figure 3.5: Representation of bracket designs (a) initial (b) topology optimisation and (c) topology and lattice optimisation. Figure 3.5a by the author, Figures 3.5b,c adapted from (Altair, 2018).

As can be seen from Figure 3.5, different kinds of optimisation can be used to create optimised designs via material removal. Figure 3.5b shows a topology optimised design and Figure 3.5c shows a combined topology and lattice design optimisation. Better functioning components with enhanced aesthetics and longevity can be created by comparing design optimisation methods based on the design constraints and defined working conditions. A modification of constraints and design goals for comparable design optimisation will be needed to select the optimal design to achieve satisfactory efficiencies. Simulation tools can be used for topology and lattice design optimisation. Different simulations, design validations and documentation can be performed along the workflow to achieve a final optimised component design. Examples of design and simulation tools are shown in Appendix L1. In a study, Etteplan (2020) shows a workflow of how CFD and the finite element method (FEM) (numerical based analysis for FEA) allow the virtual study of the performance of comparable designs on pressure drop and intended loadings under which a hydraulic block would operate (see Appendix L2).

3.3.2 Simulation-driven DfAM

Simulation tools

Simulation tools use numerical data and CAD designs to virtually model real phenomena to predict performance and generate responses to achieve the desired objectives. Metal AM/L-PBF is a promising technology that can enable new designs that would otherwise be unfeasible using conventional manufacturing methods. One key technology that has helped users of AM to gain increased benefits is computer-based software. This software can be used for the seamless integration of the various work phases in the workflow of the AM process, which includes material selection, CAD model generation, design optimisation, numerical based analysis, design validating, build preparation and validation (Autodesk Inc., 2020; Engineering.com Inc., 2020; EOS, 2020b). Computer-based tools currently can be used in L-PBF for component design, build preparation, component qualification and execution of the manufacturing process (Campbell & Bourell, 2020; Chaplais, 2016; NASA, 2019) to achieve better-optimised components, cost efficiency and shortened lead time. Computer-based simulations can help predict, rectify and avoid potential defects, (such as thermal stress, distortions, cracks) to create innovative products and help plan the build process (Chaplais, 2016).

The early detection of potential production bottlenecks helps in the selection of appropriate process parameters that can achieve the required component quality. These digital tools simplify and quicken the product development process, decrease the cycle time and post-processing, thereby reducing the time to market and costs. Digital simulations offer a means of material efficiency through downsizing and light-weighting to maximise product performance (Chaplais, 2016; Culleton et al., 2017). CFD is a computer-based fluid mechanics tool that can virtually evaluate fluid flow behaviour according to physical operating phenomena. Finite element analysis (FEA) is another computer-based tool that can predict the behaviour of structural elements based on real phenomena using numerical methods. Simulation tools allow iterative design by analysing and predicting the performance of potential design options for the intended operating conditions. These tools can also be used to fine-tune selected design solutions that can satisfy the intended design problem (Corey, 2020; Etteplan, 2020) and for data preparation in L-PBF (ANSYS, 2017).

The use of digital tools can delay the cycle time if it is not well utilised. The number of iterative runs and varying specific machine process parameters can contribute to increased cycle time. A prior understanding of the available design and simulations software and their capability reduces time inefficiency and possible related difficulties. The flexibility to design optimisation with these digital tools and manufacturing components with L-PBF should not eliminate the need to consider the design rules and guidelines of AM. Simulations-driven designing must be done with the limitations and characteristics of the building process needed for successful component manufacturing.

Simulation-driven DfAM

Design optimisation is an inherent aspect of metal AM/L-PBF, which is almost always needed in all the fields of application. This takes place either to mimic nature or create unique designs with improved functionality. Optimised designs and process parameters are possible ways to achieve efficient components, material savings and energy efficiency through software development were envisioned when developing AM (Ray, 2006; Lind et al., 2003; NRC, 2014). Advancements in process-related software allow other means of communication between the design CAD model and AM system, as was forecast (NRC, 2014). The study anticipated that new digital tools could offer new ways of improving productivity. Simulation-driven DfAM refers to the application of digital design and simulation tools to create optimised component designs based on the DfAM guidelines. Simulation tools allow for easy alteration to create complex structures within components to effectively distribute material within a given design space and/or to incorporate hierarchical porosity into them. Optimisation and validation of feasible features can be achieved with simulation tools to optimise the design based on specified loads, forces, constraints and other factors. These approaches can create designs capable of fulfilling required functionalities and other performance throughout the LC of components. Additional designing is required to redesign the optimised designs to fine-tune the design to suit DfAM rules. Fine-tuning of the selected design is performed based on DfAM rules to enhance the buildability.

simulation software offers a virtual platform to study physical phenomena via swift iteration (Jaster, 2019) to preselect the best process parameter values before the actual production. Digital simulation tools can be used to speed up the process of identifying reliable process parameters. Determining effective process parameters in metal AM can help produce high-end components (Leirmo & Martinsen, 2019; Yadroitsev et al., 2015) to fulfil the required standards, integrity, functionality and as well to reduce cost and energy consumption. Different process parameters can create various process conditions that can influence the properties and quality of the final components. It is necessary to select suitable parameters to ensure that reliable and durable components are produced.

Virtual manufacturing flexibility enables pre-validation of the build process and allows the definition and selection of building parameters necessary to satisfy design intent. Prior evaluation of build process performance and the functioning of the components helps to estimate the distortion of final parts and allows refining to overcome possible challenges during actual manufacturing. Measures are needed to reduce the number of failed components or difficulties in post-processing, examine complex support structures, voids and incomplete fusion. The initial consideration of defects and ways of avoiding them to ease post-processing during the design phase saves time and costs.

The current needs and complexities of support structures can be simplified or excluded where necessary by using automated support generation. Digital software for support generation helps reduce data preparation time, eliminates human errors, saves material, reduces waste and the workload that would be required during their removal. The automation of support structure offers a means of increasing productivity. Using simulation-driven DfAM reduces risk in the design and manufacturing phases (Pradel et al., 2018). Automated support structure generation and simultaneous performance simulation, can, for example, be used to identify ways of increasing resource and cost efficiencies (NASA, 2019).

The use of simulation software such as nTopology, Fusion 360, e-Stage and 3DXpert during the early stages of design and Powder Bed Fabrication and VoxelDance for virtual evaluation of manufacturing performances help identify and manage potential drawbacks before the actual manufacturing of parts. Such a predictive engineering approach with simulation-driven DfAM reduces the time spent on physical printing, scrap metal rate and to fulfil required certification (Chaplais, 2016; Hansen, 2015) and costs. The share of the cost of making such decisions at the early stage of product development is estimated to be only 10% (Laverne et al., 2015), which could potentially affect more than 75% to 80% of the LCC of a component (Laverne et al., 2015; Materialise, 2020) These figures are based on a particular case and does not generally represent all cases as defined case scenario and machine systems differ from each other.

4 Results and discussions

The **Part I** of this thesis answers research question 1 (**R1**) based on objective 1 (**O1**) with the results of Publications 1–3. **Part II** answers research question 2 (**R2**) based on objective 2 (**O2**) with the results of Publications 4 and 5. The questions for Parts I and II were **(R1)**: How can the factors that affect the environmental aspects of sustainability of metal L-PBF be experimentally evaluated from a life cycle perspective? **(R2)**: How does the application of LCC-driven DfAM optimisations in metal L-PBF influence the economic aspects of sustainability from a life cycle perspective? The approach to finding answers to these questions and detailed results are presented in Publications 1–5. **Part III** of this thesis answers research question 3 (**R3**) based on objective 3 (**O3**) and includes industrial verification and validating of the developed LCC-driven DfAM model shown in Figure 4.9. (**R3**): Which overall model describes LCC-driven DfAM and how is this relevant to the industry? **Part III** was carried out as a discussion with an industrial representative on the usability of the designed LCC-driven DfAM model.

4.1 Summary of results for Publication 1–Publication 5

4.1.1 Results for objective 1, research question 1 and Publication 1

The studies in (**P1**, **P2** and **P3** were carried out to answer **R1** based on **O1**. **R1**: How can the factors that affect the environmental aspects of sustainability of metal L-PBF be experimentally evaluated from a life cycle perspective? The supply chain analysis evaluated the impacts starting from the raw material to delivery of final part to the end-user (customer). The aim of **P1** was to create a supply chain model of L-PBF and CNC machining based on the review data and case scenario from raw material acquisition, manufacturing phase, transportation and end-user. The input data were assumed to be for spare parts replacement. The main results of **P1** included a supply chain analysis and a preliminary LCI study. The supply chain analysis results indicated that metal L-PBF offered an option to reduce downtime in supply chains of spare parts and reduce part inventory compared to CNC machining. Raw material in the form of metal powder for L-PBF has the tendency to decrease transportation volume. Metal L-PBF was identified as offering better customisation, on-site manufacturing, thereby allowing companies to order component designs in digital format and print on demand on site. The distance between customers and manufacturing companies was also identified as being reduced in metal L-PBF, which translates into a reduction in emissions due to reduced weight, need and duration of transportation. Figure 4.1 shows the developed supply chain models in **P1**.

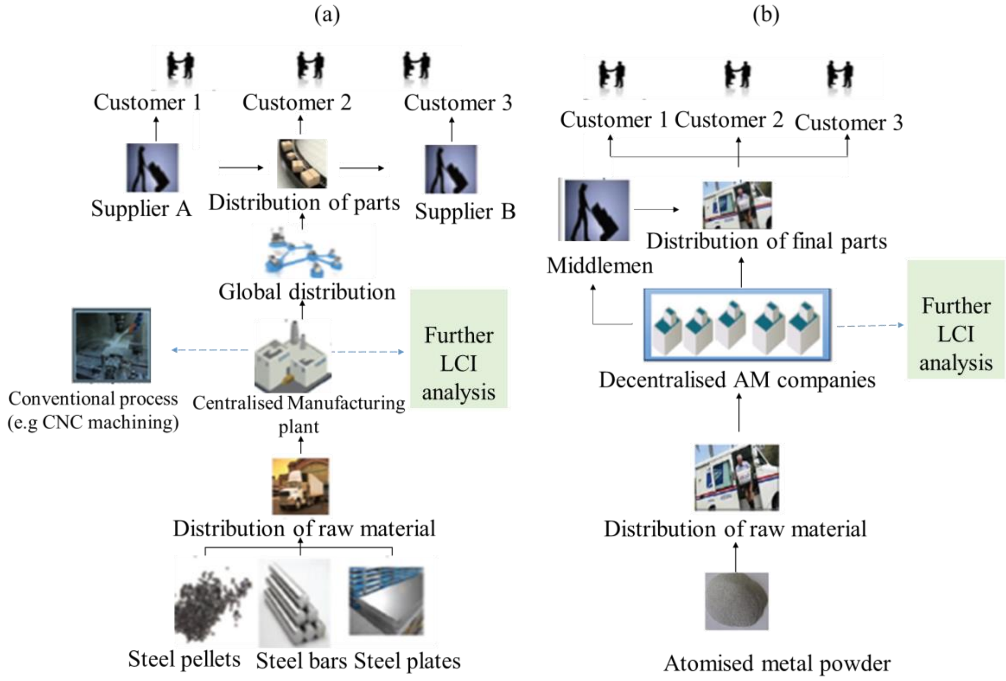


Figure 4.1: Representation of supply chain models of (a) CM and (b) AM methods from Publication 1.

As Figure 4.1 shows, the supply chain in metal AM/L-PBF is shortened with the omission of the global distribution centre and need of middle suppliers. In practice, there may be an occasional need for middle suppliers (service providers) in metal L-PBF based on the specific business model. For example, companies that are into small-batch serial production or those that may lack the capability to invest in a metal L-PBF machine may outsource the manufacturing to service providers. The weight of raw material and transportation needs in CNC machining is seemingly more compared to metal AM. The reduction of transportation needs in AM with localised manufacturing reduces the emissions associated with transportation. AM is capable to reduce production steps thereby reducing lead time and operational downtime. The preformed metal raw material used in CNC machining theoretically outweigh the metal powder used in AM.

The second part of **P1** included an LCI study as a preliminary study to identify the machine systems of both AM/L-PBF and CNC machining based on the systematic methodology CO2PE! UPLCI Initiative. The LCI analysis studied the energy (power, time), input raw material, useful outputs, waste and emissions. A detailed description of this methodology is given by (Kellens et al., 2012). The scope and studied parameters for both L-PBF and CNC machining were identified before the inventory analysis. This was necessary to define the scope of the LCI study. The results of the LCI study included the identification of machine levels, system boundaries and studied parameters for metal AM/L-PBF and CNC machining. The identified machine systems for L-PBF and CNC machining were different in terms of affecting units on identified machine levels. Figure 4.2 shows the system boundaries and main parameters that were identified in the preliminary study of both manufacturing methods.

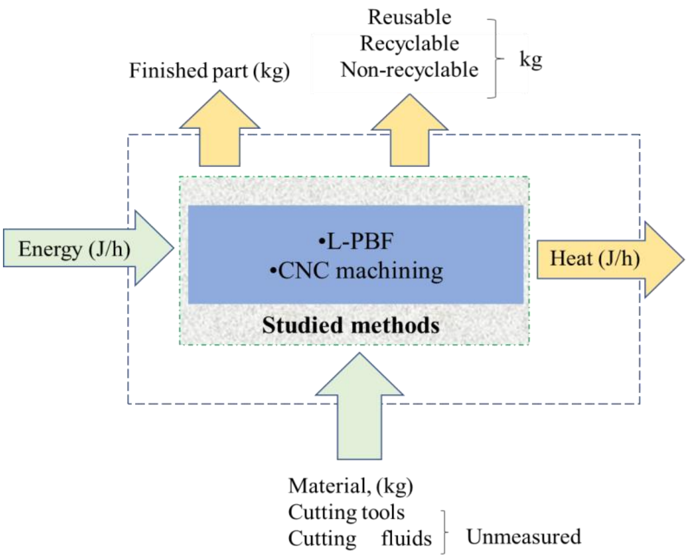


Figure 4.2: Representation of the LCI system boundaries and studied parameters used in Publication 1.

Figure 4.2 shows the scope and parameters such as inputs (materials and energy) and outputs (final component, surplus raw material and the generated heat). The levels of machine systems were systematically identified for further LCI study. These identified parameters for the LCI study were selected based on the machine levels (see Appendix M1). Two levels of machine systems were identified in L-PBF and CNC machining in **P1**. The power-driven elements that accounted for energy-consuming units (ECUs) were identified. The ECUs for L-PBF included heating units, a laser and its chiller unit, servo, scanners and the lightning system. The ECUs for the CNC machining included an automatic tool changer, spindle motors, rotating tools and cutting fluid pump motor. The identified system boundaries, machine system levels and measured parameters were used for the further LCI study in **P2**.

4.1.2 Results for objective 1, research question 1 and Publication 2

The study performed in **P2** was conducted as a practical application of CO_2PE! UPLCI methodology and to compare metal L-PBF and CNC machining based on design flexibility and effect on combined specific energy consumption (SEC*)* when multiple components are manufactured. Manufacturing scenarios were used to investigate evidence of how both methods contributed to sustainability. P2 aimed to conduct a detailed LCI study and to compare the sustainability aspects based on SEC, the material consumption and created scrap metal rate using L-PBF and CNC machining. Metal L-PBF samples were manufactured on a modified research machine representing EOSINT M-series and the machining was performed on a PUMA 2500Y CNC lathe machining centre. Figure 4.3 shows the CAD models and manufactured samples. The internal shape of samples B and C were similar in geometry. Sample B was designed as solid-walled and sample C as hollow-walled. The sample geometries used in this thesis were simple compared to the degree of complexity that can be achieved with L-PBF. The simple geometries were used in this thesis for manageable and equal comparison of the energy consumption, raw material usage and generated waste. In practice, however, the increasing complexity of components bridges the costs gap between AM and CNC machining. Detailed CAD models, manufactured components and manufacturing machines are shown in Appendix M2.

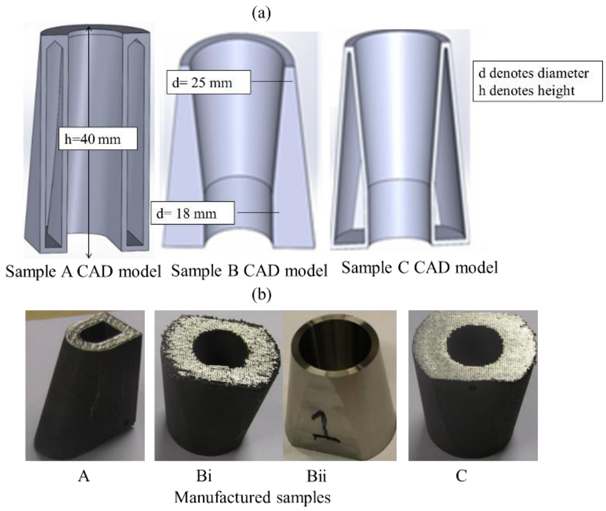
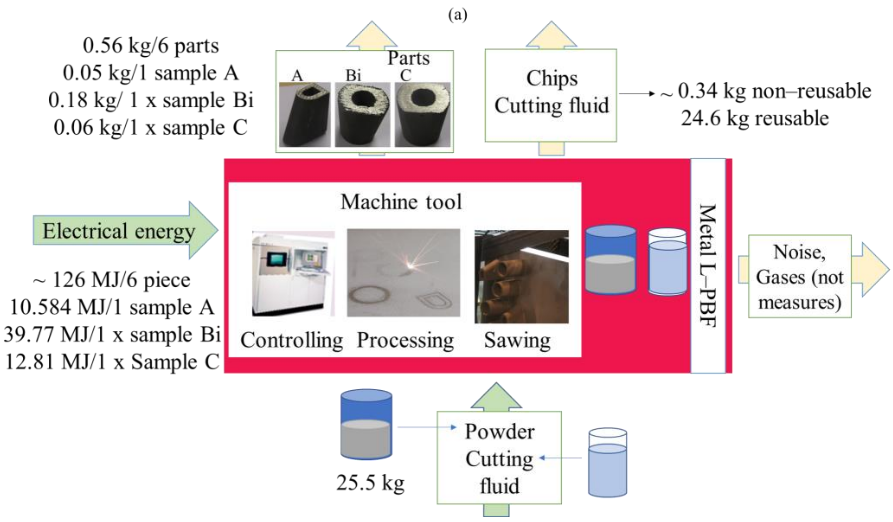


Figure 4.3: Representation of (a) cross-sectional views of the CAD models and (b) views of the manufactured components of samples A, B and C as designed in Publication 2.

Figure 4.3 shows the variance in the component designs of samples. The samples A, Bi and C were manufactured with L-PBF and Bii with CNC machining. L-PBF successfully built the hollow walled, chamfered outside geometry and sharp corners of Sample A as well the Samples Bi and C. Sample B was the only option to be manufactured with CNC machining as shown in Figure 4.3 Bii. The feasibility of machining samples A and C was assessed using simulation analysis which proved to be challenging, even if it had been possible. The result proved that using CNC machining would otherwise require extensive design modifications even if CNC machining could manufacture samples A and C.

The time taken to manufacture the sample Bi with L-PBF was much and this increased the total consumed energy during the building. This was because the design was not optimised enough to take full advantage of the process which would have reduced the build time which directly affects the energy consumption. The surface finish of L-PBF parts (Bi) was course and this is one of the main shortfalls of L-PBF. Additional post-processing is often required to sublime metal L-PBF components to the desired smoothness in terms of appearance if it would be required in the use phase. Additional post-processes to smoothen the as-built parts attract extra energy, time consumption and costs. The ability to build the optimised designs, as samples A and C with L-PBF showed the contribution to enhancing material efficiency without affecting the form and design objective. Experimental testing would be necessary in order to ascertain the level to which the different samples could perform mechanically against predefined functional requirements.

The second part of **P2** demonstrated the results of the LCI study of L-PBF and CNC machining. The results shown in Figure 4.4 are based on the identified machine levels, system boundaries and parameters in **P1**.



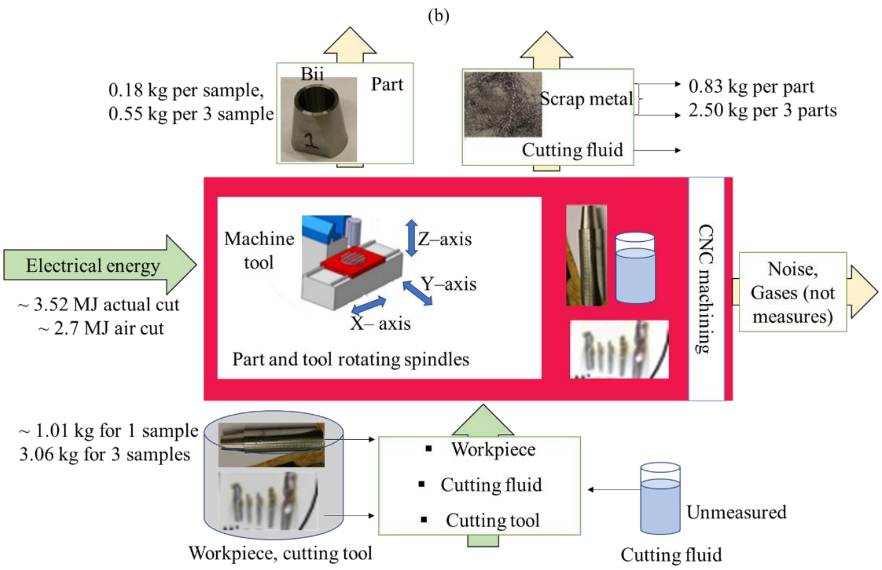


Figure 4.4: Summary of the results of the LCI study in (a) L-PBF and (b) CNC machining from Publication 2.

Figure 4.4 shows the measured ECUs, input and outputs of the comparable manufacturing methods. As can be seen from Figure 4.4, outputs such as heat, gases and noise were not measured in **P2** as they were defined within the study boundary. The results of **P2** contributed to answering R1 with the numerical values of the LCI study based on the identified system boundaries, machine levels and parameters for L-PBF and CNC machining. Machining three samples of Bii with CNC machining required three times the energy (10.56 MJ); to make one part (3.52 MJ); the same applied to the raw material (550 g) as can be seen in Figure 4.4b. The opposite was the case for metal L-PBF as the combined build on the build platform translated into better material and energy efficiency. Energy efficiency is shown with a reduced combined energy consumption as the number of parts increased. L-PBF offered a means of achieving better-optimised part geometry with improved material efficiency. The material was saved using the reduced amount of start-up powder that would be needed for separate builds. This also translated into better indirect energy efficiency in terms of the saving in the embodied energy used to produce the raw material.

The results in **P2** showed that specific energy consumption (SEC) for making samples was high in metal L-PBF. A comparable analysis of energy consumed for making one of sample B was almost ten times in L-PBF (39.9 MJ) compared to the quantity consumed to manufacture one sample B using CNC machining (3.52 MJ). It is worth stating that the experimental study was carried out using a modified version of the L-PBF machine. Therefore, the energy consumption does not represent the industry perspective. The high energy consumption in metal L-PBF however agrees with the similar observation of Liu et al. (2018); Sharif Ullah et al., (2015).

The result of the LCI study included a scenario-based analysis of specific energy consumption for metal L-PBF and CNC machining for making only sample B. Estimation of the effect of the batch size on specific energy consumption is based on computer data. The scenario for metal L-PBF was based on simultaneous manufacturing of an increased number of parts to efficiently utilise the build platform. Figure 4.5 shows the result of the comparison of specific energy consumption for metal L-PBF and CNC machining.

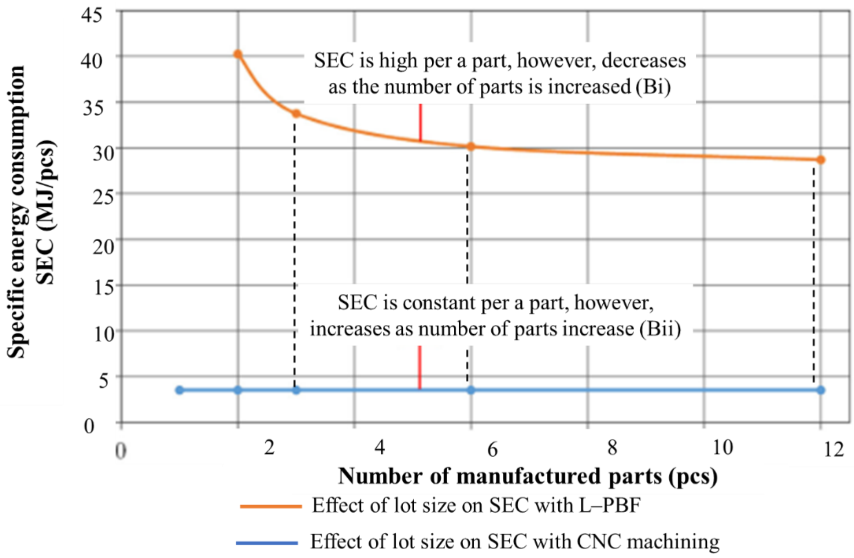


Figure 4.5: Overview of the effect of batch size on specific energy consumption for manufacturing sample B with L-PBF and CNC machining.

The SEC per part for metal L-PBF was high, whereas CNC machining energy was low and constant. The combined value of SEC in metal L-PBF offered a decrease in SEC (dividing SEC per number of components on build platform) whereas combined CNC machining values increased with multiple part manufacturing. The combined SEC in CNC machining was estimated as a product of the individual SEC per one sample of Bii and the number of components that were manufactured. Figure 4.5 showed a reduction in SEC for metal L-PBF with the combined build of multiple Bi parts. This was because the amount of electrical power consumed by, for example, heating units, spreading powder, moving the build platform, laser chiller unit, servo motors and lightning system remained constant, irrespective of the number of manufactured parts. The scenario-based case showed that metal L-PBF could reduce raw material and energy consumption by combined manufacturing. Machining of the sample Bii on the other hand required the same amount of electrical power to separately machine multiple numbers of sample Bii.

The trend of SEC per estimated number of components shown in Figure 4.5 indicated that increasing the number of parts improves energy efficiency in metal L-PBF. Increasing the number of components in CNC machining showed a constant specific energy consumption per part, whereas SEC values decreased with multiple parts in L-PBF. The high energy consumption in metal AM can therefore be controlled by optimising the process parameters and build platform utilisation. The varying energy consumption in metal L-PBF confirms the observation of Sharif Ullah et al. (2015).

Some aspects of sustainability were identified to be better in metal L-PBF than in CNC machining based on the results of the scenario-based case in **P2**. Metal L-PBF offers optimised lightweight components and flexibility of an integrated design manufacturing. Metal L-PBF enables better material utilisation, the absence of cutting tools (see Figure 4.4) reduced manufacturing steps, the extensive need for process fluid and reduces waste. Waste is reduced in metal AM/L-PBF compared to CNC machining through better material usage, reduced scrap and process fluids. The assumption and empirical results of better material efficiency in metal AM/L-PBF, as can be seen from Figure 4.4, correspond to Najmon et al. (2019); Salmi et al. (2016); Serres et al. (2011).

The results of the **P2** does not present the benefits such as post-consumer use value in this study. It is however presumed that EOL metal components are suitable for repairing, remanufacturing, recycling and recovering after their useful life. The LCI study in the **P2** result does not also include empirical measurement of created emissions.

4.1.3 Results for objective 1, research question 1 and Publication 3

P3 aimed to understand general process phenomena and to investigate the effects of process parameters on feature sizes and for their characterisation in metal AM/L-PBF, as well as to understand the potential effect of pulse laser (L-PBF(P)) emissions on the quality of stainless steel 316L components. Figure 4.6 shows the influence of the process parameters and wave type on scan track quality. Refer to Appendix N1 for the process parameters used and the manufactured samples.

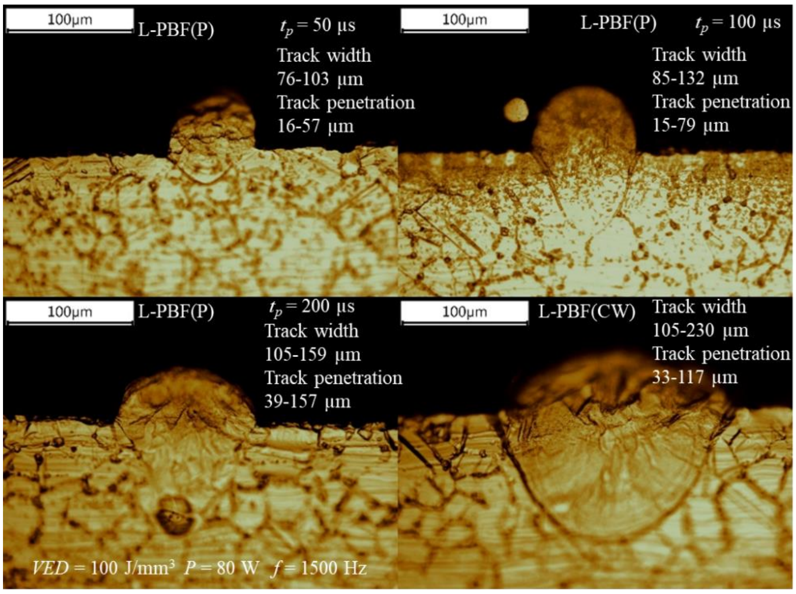


Figure 4.6: Representation of comparative tracks quality and dimensions for the different pulse lengths of L-PBF(P) and L-PBF(CW), (image copyright Laitinen, V.).

The results of this study (see Figure 4.6) showed that different process phenomena influenced differently the formation of melt pool and feature size of the single tracks. Using a sufficient laser power value at the right scanning speed maintained a stable melt pool. The results of the study showed, for example, that the values of the pulse length (50, 100, 200 µs) at varied scanning speed values (9–489 mm/s) and a constant value of *VED* decreased the width of the tracks and their penetration into the substrate. The results of the study showed that an increase in scanning speed at a constant volumetric energy density resulted in a decreased width and penetration depth of the single track of both L-PBF(CW) and L-PBF(P) emissions. The study also showed that the scanning speed values were constrained by pulse lengths (50 µs, 100 µs *and* 200) and the maximum pulse repetition rate (2 kHz). Additional overlapping of approximately 0.55, 0.30 and 0.20 a.u. respectively, for pulse lengths 50 µ*s*, 100 µs *and* 200 µs, by increasing the repetition rate, were required to form continuous tracks. Samples built with L-PBF(P) showed narrower tracks compared to samples built with L-PBF(CW) emission. The formed single tracks with L-PBF(P) were narrower than the ones built with L-PBF(CW) as seen in see Figure 4.6. The experimental and theoretical findings of the studied process parameter values and L-PBF(P) showed that the pulse length largely controls the melt pool to produce tracks of high spatial resolution.

Different optimised process parameter values can be selected to control defects and result in good track quality which can result in better material and energy consumption. L-PBF(P) emission is proven to produce finer feature size and spatial resolution in single tracks in metal L-PBF. The modified AM machine used for the experiment to an extent differs from the industrial L-PBF machine that could influence the outcome of this experiment. For instance, the L-PBF(P) test pieces were built with a continuous scanning movement of the laser beam instead of the industrial practice of the ‘point-and-shoot’ approach. The results of **P3** therefore cannot be generalised for all L-PBF systems as industrial AM systems may have different flexibility to process phenomenon. The findings of **P3** nevertheless correspond with the studies of Brock et al.(2014); Fayazfar et al. (2018); Yadroitsev et al. (2013).

The selection of optimised process parameter values to control for potential defects in L-PBF resulted in material efficiency and cost reduction. The process parameters and wave emission can be used to control melt pool formation of metal L-PBF for improved component reliability and cost-effectiveness. The possibility to use L-PBF(P) to manufacture narrower tracks is promising to build thin walls with enhanced quality. This shows the possibility to manufacture fine-featured (small and delicate) components with L-PBF(P). L-PBF(P) emission shows potential for improving the spatial resolution in L-PBF processing. Careful consideration of energy peak and pulse length is required to avoid undesirable defects if the ‘point-and-shoot’ approach is used.

4.1.4 Results for objective 2, research question 2 and Publication 4

P4 was conducted as a review, case studies and scenario modelling to answer **R2** based on **O2**. **(R2)**: How does the application of LCC-driven DfAM optimisations in metal L-PBF influence the economic aspects of sustainability from a life cycle perspective? **P4** aimed to provide a deeper understanding of LCC and how DfAM could be utilised to reduce the cost of metal AM/L-PBF. The focus of the study was to highlight cost-efficacy throughout the entire life span of metal AM/L-PBF manufactured components. The result of **P4** was a model that combines the benefits of the DfAM guidelines and simulation-driven tools during the design and builds phases. Simulation-driven tools allowed the creation of optimal and efficient designs, as well as the selection of the best process parameter values. The developed LCC-driven DfAM model is illustrated in Figure 4.7.

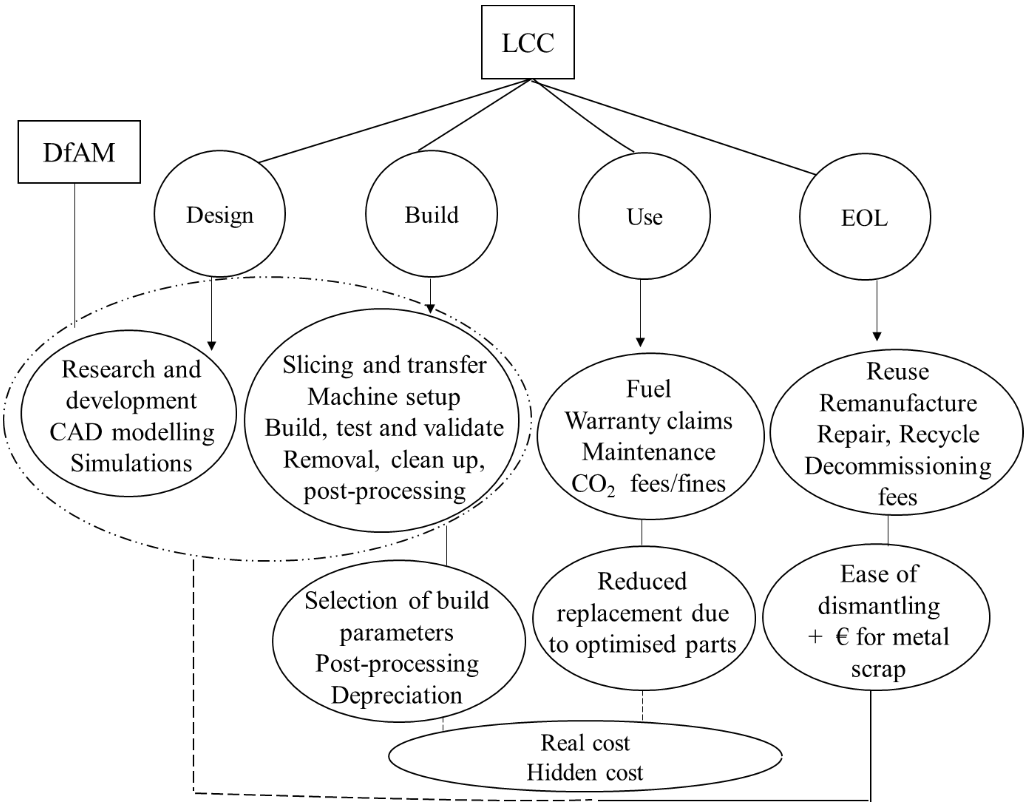


Figure 4.7. Representation of the developed LCC-driven DfAM model in Publication 4.

The LCC-driven DfAM model in Figure 4.7 includes activities at the various LC phases that can be used to achieve improved cost-efficiency. The overall cost-benefit of the entire life span of built components can be enhanced. An initial model for accessing the life costs included the different LC phases and the main cost drivers (see Appendix N2). The study resulted in an integrated LCC-driven DfAM model based on activities that could support cost reduction and support decision-making in metal AM/L-PBF. The results of **P4** show four main approaches to how simulation-driven DfAM can be used to reduce inefficiency in metal AM/L-PBF. The study showed that cost-efficiency achieved could be achieved by reducing time, raw material and energy consumption, generated emissions, as well as other identifiable parameters. The application of simulation-driven DfAM was identified as an efficient method for improving product design for metal L-PBF. The results also showed that simulation-driven DfAM in L-PBF can be used to create energy-efficient designs, enhance part functionality and cost-effectiveness, which corresponds to the study by Simpson (2020); Etteplan (2020).

4.1.5 Results for objective 2, research question 2 and Publication 5

The study in **P5** was conducted with data from the existing literature to answer **R2** based on **O2**. This study aimed to highlight the benefits of metal AM/L-PBF in fields other than the commonly publicised applications. The review on metal L-PBF in the electrochemical field included flow reactors, electrical discharge machining (EDM), electrochemical machining (ECM), substance detection and rechargeable batteries (REBs) applications. The results of this study showed that metal AM/L-PBF was capable of effectively manufacturing optimised electrodes for these electrochemical applications. The results from the review data showed that metal L-PBF electrodes had the potential to enhance electrochemical efficiency because of increased surface area and improved mass transport. Practical cases of how the integration of tortuous and lattice structures can be built from a single material or from multiple materials to enhance an integrated functionality of electrochemical separation units. Some of the cost-effective raw material that could easily print electrodes did not have the suitable characteristics necessary to achieve the required functionality. These limitations were overcome by improving the surface properties of the printed electrodes. This was achieved by coating the printed electrodes with functional materials to form multi-material electrodes. The cost reduction in terms of making optimised designs and functionally modified electrodes resulted in improved process efficiency with nearly all the collected data from the literature. The main findings of **P5** that support the design optimisation and cost reduction in the manufacturing and use phase of electrodes are shown in Table 4.1.

Table 4.1: Summary of the research case studies.

Application	Materials	Results	References
EDM tool electrode	• Bronze–nickel alloy • Pure copper (Cu) (~50 µm) • Stainless steel alloy (DS20 (~20 µm) • A mixture of 50/50 vol% pure Cu and 50 standard EOS steel alloy AlSi10Mg • Tungsten carbide cobalt	• A complex flush channel was designed • Optimal properties of bronze-nickel • Less time and costs in manufacturing	(Amorim et al., 2013) (Sahu & Mahapatra, 2020) (Uhlmann et al., 2018)
Substance detection	• Stainless steel, iridium oxide (IrO_2) film-coated • Stainless steel, gold (Au) coated • Stainless steel Bismuth (Bi) coated • Stainless steel, Au coated	• Sensitivity to phenol and p-aminophenol (p-AP) detection was achieved. • An Au coated electrode improved both acetaminophen and dopamine detection. • The sensitivity of the Au coated electrode increased 4.7 times	(Ambrosi et al., 2016) (Cheng et al., 2017) (K. Y. Lee et al., 2017) (Liyarita et al., 2018)
ECM	• Powder mixture (70 wt.% alloy steel (42CrMo4), 20 wt.% Cu-Tin alloy (CuSn8) and 10 wt.% (Ni)	• L-PBF built lattice-like metal electrodes offered a vigorous flow for the electrolytic fluid • Optimised lattice structures enhanced electrode performance • The electrolyte flow rate for increased machining rate was improved with optimised L-PBF electrodes	(Koyano et al., 2017)

(Continued overleaf)

Table 4.1 continued.

Application	Materials	Results	References
Flow reactors	• Stainless steel, Nickel (Ni) coated • Stainless steel (X2CrNiMo 17-12-2)	• Customised scaffold-like electrode, better functionality than comparable conventional planar electrodes • Enhanced surface area and porosity of the electrode • Consolidated design of electrode and the current collector • L-PBF electrodes improved the mass transport coefficient by 76%	(Arenas et al., 2017) (Lölsberg et al., 2017) (Heiskanen et al., 2020)
Water splitting	• Austenitic stainless steel, Ni film • Stainless steel, Pt film • Stainless steel, IrO2 film • Stainless steel. • Stainless steel, Ni-Fe film • Stainless steel, Ni-MoS2 • Stainless steel (AISI 316L stainless) • Titanium (Ti), TiO2 nanotubes	• Increased anodisation performance • L-PBF allowed the control of pore distribution, sizes and geometry compared to the conventionally manufactured electrodes. • Improved mechanical properties with L-PBF electrodes • An L-PBF built cellular stainless steel (CESS) electrode improved corrosion resistance with electronic conductivity and mechanical properties in an alkaline electrolyte	(Ambrosi & Pumera, 2018b) (Ambrosi & Pumera, 2018a) (Huang et al., 2017) (C. Y. Lee et al., 2017)

(Continued overleaf)

Table 4.1 continued.

Application	Materials	Results	References
REBs	• Ti (Ti6Al4V), polypyrrole PPy, film • Al alloy AlSi12 • AlSi12, SiO2 nanoparticles	• Enhanced charge transport • Increased electrode surface area and battery charge capacity • Successful adherence of SiO2 nanoparticles to an L-PBF electrode using the Sol-Gel method for the elevation of intercalation of Lithium (Li) ions • Enhanced kinetic diffusion and ion transport by pore size and mass distribution	(H. Sun et al., 2019) (C. Zhao et al., 2014) (Chiu et al., 2020) (Jha et al., 2020)

The results of the review shown in Table 4.1 highlight some of the potentials that are achievable with L-PBF. Metal L-PBF offered cost-effective, durable components with multi-material attributes. The surfaces of the printed metal electrodes were functionally modified to form multi-material electrodes to satisfy the expected functional requirements. The new features positively contributed to the mass transportation, electrical and thermal properties, which have the potential to increase productivity. The **R3** and **P5** contributed to the understanding of unlimited design flexibility (for example finer-featured parts, part consolidation, lattice and tortuous structures) that are attainable with metal AM/L-PBF for electrochemical separation units. This highlighted the possibility of making components with increased functions of intricate internal features, which corresponds with the findings of Ortona et al. (2012); Tan et al. (2018). The findings of the study showed that costs reduction was possible with optimised electrodes. Integrating new designs into existing electrochemical units, as well as creating new optimised and customised electrodes are possible without increasing cost.

4.2 Analysis of the findings based on the thesis summary

The discussion part of this thesis is divided into three sections based on:

- Impact of strategic business models on metal AM/L-PBF
- The outcome of industrial verification and validation of the developed LCC-driven DfAM model
- The benefits of simulation-driven DfAM for sustainable manufacturing and the CE

These results fulfil the aims of the thesis and give an overview of how sustainability and the CE can be enhanced in the industrial sectors with the adoption of metal AM/L-PBF. An assessment of the industrial applicability of the LCC-driven DfAM model along the value creation chain was performed to help identify the most optimal application to the adoption of metal L-PBF. Conclusions drawn from the discussion with industrial representatives were used to modify the LCC-driven DfAM model.

4.2.1 An all-inclusive operating and LCC-driven DfAM model

Many large and medium-sized companies adopt AM by expanding their existing production lines. Other companies start as new small and medium enterprises (SME) while others emerge and remain in the research field. The business dimensions (administration, marketing and sales) along the manufacturing chain tend to be more profit-orientated and will often adopt innovations with projections of swift profits. The business defines the corporate objectives and makes decisions based on a business strategy. The engineering dimension defines the core components and creates detailed designs based on the principles of DfAM. A business-centric approach can and often will, direct the requirements of core products based on market needs, which can result in making more customer-centred components. Industrial business and engineering activities complement each other in real life. The inclusion of an intersecting parallel model of profit-centric and science-centric to the LCC-driven DfAM model (see Figure 4.8) will help identify the effective use of the LCC-driven model.

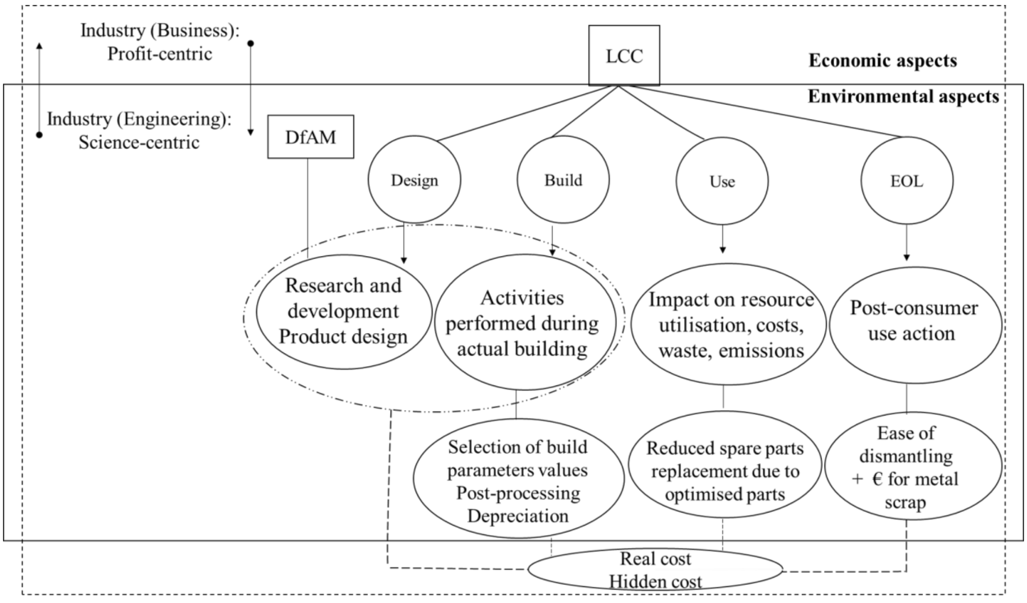


Figure 4.8: Representation of the practicable relationship between business and engineering models to validate further development of the LCC-driven DfAM model.

As can be seen from Figure 4.8, engineering activities define the core components based on the principles of DfAM. The engineering activities is supported by the business activities. The choices made during product engineering influences functionality of the components, resource consumption rates, waste and emissions creation. The engineering activities mostly controls the environmental aspects. The area that encompasses business occupies a broader part of the model as the daily functioning of industries is closely associated with administration, marketing and sales. The activities of business direct the requirements of core products based on market needs and control the overall costs (economic aspects). The core product (tangible) and services (intangible) both contribute to controlling the LC costs of components. While engineering is science-centric, business is revenue and commission-centric. A combination of both approaches could potentially improve customer satisfaction and help achieve the financial targets of industrial companies. The potential pairing of the two dimensions could result in the satisfactory performance of industries and the satisfaction of customers.

The warranties and guarantees that car manufacturers promise their customers could, for example, be maintained without compromising sustainable competitiveness. OEMs often manufacture physical parts and store them to meet the supply chain demands of conventional manufacturing. Some of these components often end up not being sold or no longer required in the market. Component-specific moulds and tools may also become redundant or require some sort of remanufacturing into a usable state for other components. The digital value chain offered by AM supports the use phase, for example, in the automotive industry in which customers often want the quick replacement of spare parts.

4.2.2 Reviewed and verified model of LCC-driven DfAM

Certain steps are necessary to successfully adopt metal AM/L-PBF, regardless of the level of entry or mode of application. Companies need to consider the overall benefits of an assembly if the component is intended for larger machine assembly. This will help in deciding whether using metal AM/L-PBF will be useful to the total functionality of the machine. The developed LCC-driven DfAM model was modified to cater for industrial considerations using a step-by-step approach. The aim was to refine the final model to include specific industrial expectations. A first and second revision was carried out to analyse the suitability of the developed LCC-driven DfAM model (see Appendix O). The emphasis was on the product design and the overall benefit of simulation-driven DfAM along with the various LC phases. The verified and validated LCC-driven DfAM and the potential benefits for metal AM/L-PBF are illustrated in Figure 4.9.

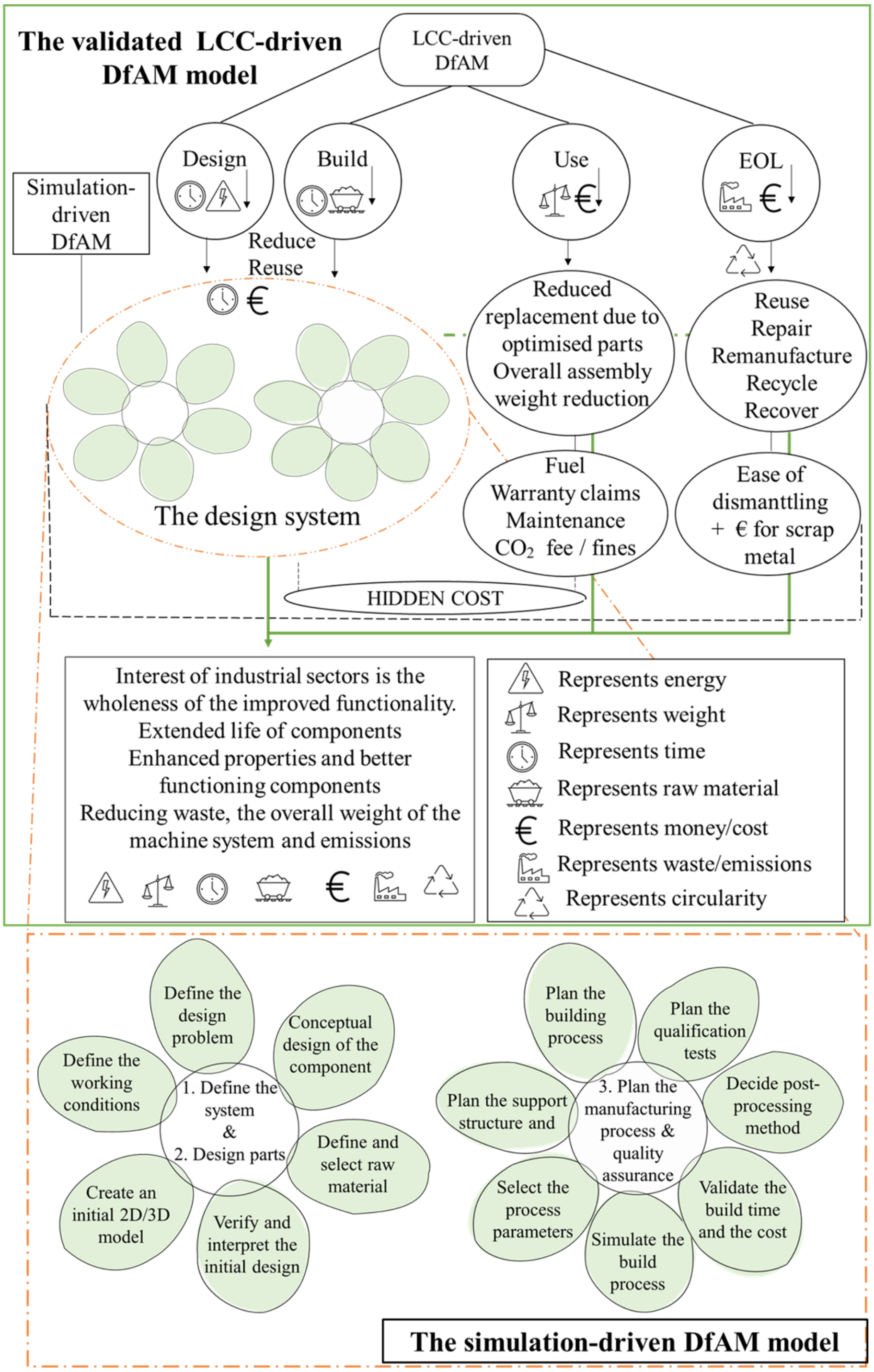


Figure 4.9: Representation of revised-driven DfAM model based on industrial validation.

As can be seen from Figure 4.9, simulation-driven DfAM can be used to control both the design and build phases in the LC of metal L-PBF components. The industrially modified LCC-driven model (shown in green area) included a detailed product design relating to simulation-driven DfAM (shown in orange area) in controlling the overall costs. Digital software can be used to design optimised components with increased functionality, added value and reduced costs throughout the LC if it is correctly implemented. The identified benefits of the design system (designing and manufacturing) to improved functionality and efficiency (shown in Figure 4.9, green lines). These improvements can also result in optimising other components designs of a larger system. The reality of controlling energy, weight, time, raw material and cost efficiency is attainable with proper adoption planning. The implementation of L-PBF and other AM subcategories must be considered in terms of four main value-added benefits. Firstly, the aim should be to optimise the design and to consolidate parts to reduce part count. Secondly, the aim should be to achieve customised and lightweight components. Thirdly, the aim should be to make complex components where using a conventional method may be uneconomical and technologically impossible. Fourthly, the aim should be to create more efficient designs with swift manufacturing, reduced manufacturing steps, extended service life, cost-efficiency, as well as reduce waste and emissions. The developed model is expected to serve as a guide to help make informed choices for decision-making in other AM methods.

The benefits and risks of metal AM/L-PBF can be case-specific. Thus, two manufacturing proposition scenarios were considered following VCA and SWOT analyses (see Appendices P and Q), respectively. The three aspects of sustainability can be considered in all activities of the VCA. Companies that outsource production and design to service providers may do so to the detriment of sustainable goals and data security. This is more likely to happen in companies that outsource part of their core activities compared to companies that handle all their core activities. Subcontracting companies may not be committed to sustainable manufacturing strategies. Companies that use such a business strategy must ensure that their service providers operate to a certain level of internally set CSR goals in compliance with the SDGs. A SWOT analysis can help gain a better understanding of how metal AM/L-PBF may be used to generate the most optimal competitive advantage and reduce the negative impact for companies and customers (end users). Strengths and weaknesses must be considered internally whilst opportunities and threats are externally analysed.

<u>Strengthen advantages and take measures to reduce weaknesses</u>

Establishing internal working mechanisms and defining the responsibility of the respective departments such as development and design teams, purchasing office and management, can enhance adoption. Strategic measures must be taken to ensure that the planned objectives are met by appropriating and strengthening supervision. Companies must take positive measures to eliminate weaknesses. Internal weaknesses can be overcome by taking proactive measures. Continuous investment in resource-efficient, education, training in process-specific technologies and good strategic communication (see Appendix R) can be used to turn weaknesses into strengths. Strengthening cooperation with stakeholders and service providers can provide a healthy working environment for continuous growth. Optimising any of these can potentially improve operational efficiency and reduce costs. Operational efficiency is a primary metric that measures the efficiency of output profits in relation to the expended inputs.

Identify the opportunities and take measures to reduce threats

AM companies are expected to grow beyond their current capabilities. Companies can take initiatives to benefit from pre-emptive opportunities. Forecasting and planning to meet future demands will give companies a competitive edge, as well as increase their technological and industrial advantages and provide opportunities to excel in future markets. Forward-thinking scenarios can be used by companies to create future business cases and potential solutions. This will provide swift solutions to problems when they become a reality. The mapping of prospective customers and markets can help provide information that could promote future designs and material development. The current customer segment might be diverse, thereby increasing the logistics chain. Proactive measures for future expansion as the technology matures to become part of mainstream manufacturing can help in swiftly responding to such anticipated and inevitable changes.

4.2.3 Results for simulation-driven DfAM on sustainability

The use of metal L-PBF has the potential to enhance sustainable manufacturing with the application of DfAM principles and digital (designing and simulation) tools. The benefits of customisation, part consolidation, light-weighting, downsizing, improved functionality, durable components, better resource efficiency, shortened supply chains, easy accessibility and waste reduction are AM-specific offered enablers to increase environmental efficiency and economic efficacy. The benefits such as the possibility of improved wellbeing, new research field and co-creation are some of the presumed social effectiveness benefits offered by metal AM/L-PBF. The social aspects of sustainability were not much studied in this thesis due to the scope of the study.

Environmental efficiency can be achieved with reduced resource consumptions and reduced wastes. Designing optimised lightweight and efficient components with L-PBF can reduce cycle time, material consumption and energy utilisation thereby increase profitability. Efficient utilisation of build platform to full capacity can reduce SEC and costs. Automatic part positioning to build a platform, for instance, can help identify the best position and alignment to reduce the need for support structures and the quantity of support materials (Praet, 2017). The automation of part placement reduces production time and costs (Salmi et al., 2016).

Economic efficacy can be achieved when input factors produce the needed productivity. Using digital tools offer effective means to optimise components. Optimised lightweight components have improved functionality and potentially reduce fuel required during the use phase. Optimised components can outlive the estimated lifetime thereby reduce the number of replacement parts and repairs needs. Digital tools and AM enable the swift replacement or repairing of old or broken components with a new part or via surface coating without the need to replace the whole components. This also improves costs and promotes the economic as well the environmental aspects of sustainability as resource usage and related waste for making new components will be minimised.

Social effectiveness can be achieved when the available knowledge and skills of personnel are utilised to achieve needed results. Lack of coherent collaborations may affect the successful usage of skills and therefore unequal distribution of benefits and burdens within the company in the long run. There could be overused or underused skills within a company, this requires balancing in other to reach proficient utilisation of resources for the needed social equity. The potential of digital tools for social effectiveness requires additional studies to ascertain its convenience.

Simulation-driven DfAM enables a transition to new digital sustainability by enhancing efficiency, effectiveness and efficacy via electronic data in relation to sustainable manufacturing. Simulation tools offer the potential to the digital value chain to improve environmental and economic benefits throughout products LC with more resource-efficient components which also reduces waste and emissions creation. Figure 4.10 illustrate how digital design and simulation tools can be used to enhance sustainability.

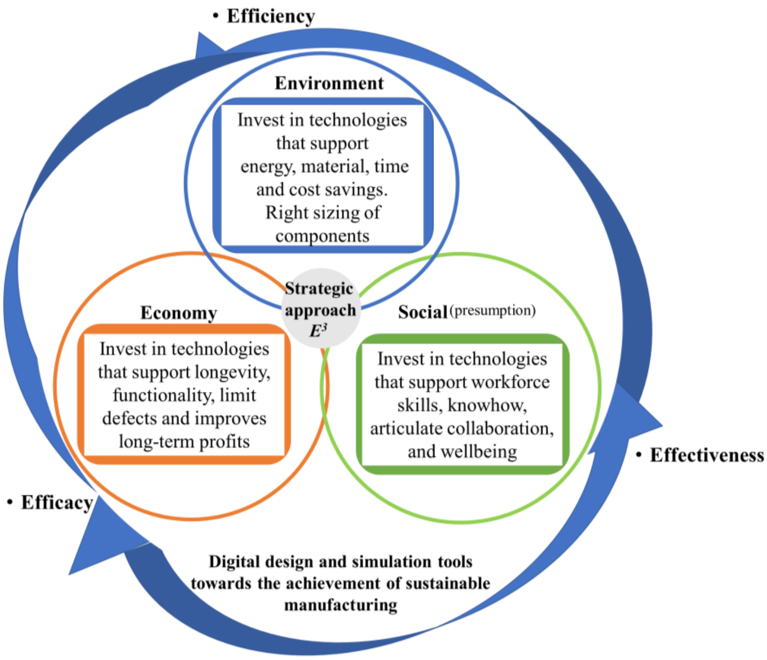


Figure 4.10: Representation of how digital design and simulation tools can be used to improve sustainable manufacturing.

Figure 4.10 illustrates how the use of simulation-driven DfAM can be used to optimise product design towards achieving the three pillars of sustainability. The possibility of iterating design performance virtually to reduce part failure helps to reduce defects and costs. Improving on the results of a previously performed iteration enhances performance, durability and reduces costs. The use of computational methods during the design, development and validation phase of the design and manufacturing of components reduces waste and eliminates other inefficiencies when a virtual platform is used. The 6R approach alone cannot offer the necessary change for enhancing circularity in manufacturing. Components designed for metal L-PBF can be optimised for achieving extended product life and an extension of 6R. Figure 4.11 shows the LC phase and the extended multi-R approach model for metal AM/L-PBF.

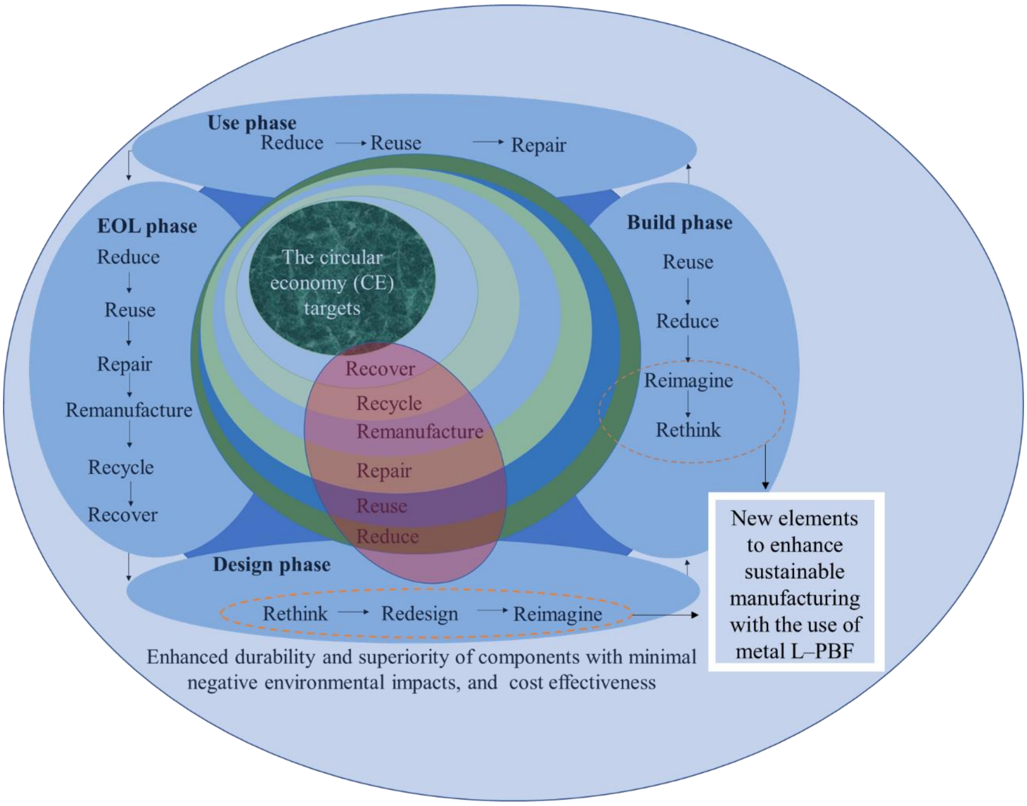


Figure 4.11: A multi-R approach model to enhance circularity in L-PBF.

The four phases (design, build, use and EOL) of L-PBF as seen in Figure 4.11 interconnect with each other. This is how modern manufacturing should operate in order to enhance sustainability. The area encompassing the 6Rs (red region) in Figure 4.11

reduces according to the preferred outcome. Metal AM/L-PBF enhances material and energy efficiency by way of material reduction, reuse, recycle, as well as reduced direct and indirect energy consumption. An overview of the entire value chain highlights that metal AM supports extended product life via reuse, repair, remanufacturing, recycle and recover and for controlled environmental emissions and emission-related fines, where applicable.

Rethink and reimagine: The creativity of designing engineers for components design is not adequate to envisage design possibilities. There is flexibility to create intricate designs without having to first consider tools/mould/machine constraints. Flexibility to design high-value components with enhanced functionality and cost-effectiveness is attainable as an increase in complexity incur no extra cost (Fraunhofer, 2016). Several studies have recommended substituting AM with conventional manufacturing where intricacy, lightweight, customisation and on-demand products are uneconomical and unfeasible (Klahn et al., 2014).

Redesigning: Refers to the changing of model, materials, or technology to enhance the valuable use of the product. For example, designing components with consideration of reuse, repair and remanufacturing options will extend product life, save cost and protect the environment. The function of redesigning components as part of a larger assembly can also influence the design of other components which may be manufactured via conventional manufacturing methods. Substituting a component material with comparable material with better printability sometimes can enhance technical superiority and reduce cost than would be with originally indented materials. The manufacturing of aluminium grade 6000 or 7000 series powder for example can be susceptible to crack at the exposure of laser energy. Manufacturing components with such materials with metal L-PBF may require a change in design and material. Design and materials change that can give the needed properties for reduced scrap, improved functionality, extended lifetime and reduced lifetime cost of end component will enhance productivity. This is the point where engineers will have to rethink redesigning the component for metal AM/L-PBF.

Reduce: Refers to the reasonable utilisation of money, energy, raw material, time, process aids and other resources. Reducing raw material and energy usage will increase economic and environmental effectiveness. Conventional machining methods often removed a large part of input material as scrap in while metal L-PBF can build parts by using just the required quantity.

Reuse: Refers to the tendency of being able to use again a material or product. Metal L-PBF enables the reuse of powder within the build phase. The unfused powder can be mixed with virgin powder materials for a new build. Metal components usually are reusable post-consumer use. Post-consumer use and broken components which have come to the end of service life may directly be reused or reconditioned via repair and remanufacturing.

Repair: Refers to restoring damaged components by fixing or replacing them with new parts for continuous usage. As earlier mentioned, metal AM can be used to replace broken parts of components via a reverse engineering. This approach is an efficient way to reuse functional components which may be faulty without necessarily making a whole new component.

Remanufacture: Refers to the reprocessing of post-consumer use products by reusing old parts and functionality to form new parts to original form and state. This approach is an effective way to enhance material efficiency as old parts can be used to create new products thereby reducing the need for new components. Metal AM allows for remanufacturing via directed energy deposition or part replacement with L-PBF.

Recycle: Refers to the process of converting out of service life products into useful materials or new parts that would otherwise have been thrown away. The recyclability of a material depends on the ability to recondition recovered materials to required properties as desired of the virgin option. The recycling of EOL components the environment by reducing the amount of consumed raw material, energy and released pollutions that are characterised by virgin material processing. Recycle also reduces the amount of waste that ends up at landfills and incinerators.

Recover Energy: Energy recovery refers to any method that can minimise the input of overall energy into a system by converting waste into usable energy from one sub-system to another. The heat generated in metal L-PBF can for instance be converted to energy for heating purposes. Materials that are non-recyclable at EOL can also be converted into electricity.

All elements of the multi-R approach must be maintained during the design, build, use and EOL phases. Certain elements will downplay in one phase than the other as not all the elements are achievable at every stage of the LC. Efforts to enhance resource efficiencies via the CE target (reuse, repair, remanufacture, recycle and recovery) can help achieve both environmental and economic sustainability to promote SDGs goals. The achieving of the 6Rs with metal AM/L-PBF affirm that this method is a feasible option for sustainable manufacturing according (Hibbard, 2009; Kishawy et al., 2018). The introduction of the additional ‘Rs’ in the 6R approach serves as a pacesetter to rethink designing and the applicability of metal AM/L-PBF to support the creation of more sustainable processing and components.

5 Conclusions

Sustainability represents an environmentally, economically and socially competitive advantage that offers companies a strategic approach to success. Sustainability in the manufacturing sectors must be considered as a concept that offers pathways to achieving both business and legislative goals. Setting corporate sustainability goals and the use of strategic plans for value creation can help companies gain a holistic view of the choices and decisions that can be applied to making high value and better functioning components. The sustainability aspects of metal AM/L-PBF can also attract and motivate new users as it has become a part of every industrial sector.

The sustainability aspects in metal AM/L-PBF are often discussed from the material efficiency and the potential to manufacture energy-efficient components. The quality of components is also an integral part of ongoing discussions on the application of metal AM/L-PBF. Time-intensity and the start-up cost are mainly the basis of industrial discussions. The costs of metal L-PBF is industrially perceived as high and the processing as time intensive. Some of the key causes to why companies may hesitate to re-design with metal AM/L-PBF are the high investment cost (includes hardware, software, raw material), part size limitation, vast controlling process parameters, limited material choices, lack of knowledge, qualification and certification. The characteristics of metal AM/L-PBF can positively or negatively influence time and costs as illustrated in Figure 5.1.

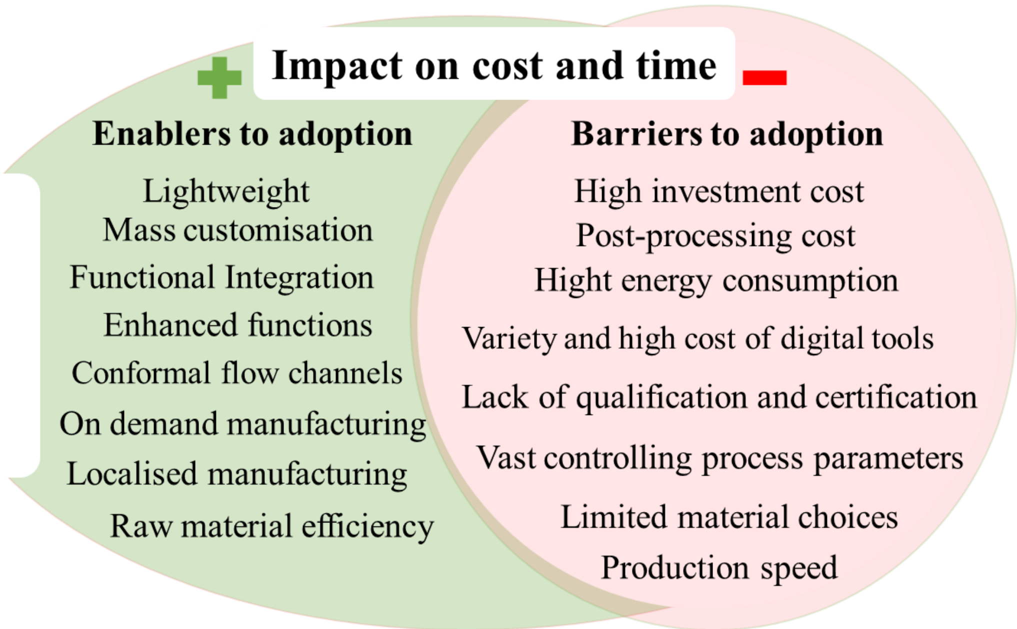


Figure 5.1: Illustration of key factors to the adoption of new ideas (for example metal AM) in industry.

As can be seen from Figure 5.1, cost burdens and time-intensity can block the entering stage to new ideas in industrial sectors. The initial investment cost, the machines, operating cost (for example, raw material, salaries, utility) and cost required for activities in the early stage (machine setup, test runs, training) are examples of cost burdens that may hinder the acceptance metal AM/L-PBF. Some of the activities that are time-intensifying in the early stages of metal AM/L-PBF may include feasibility studies, training and the learning of principles of DfAM. Time is a critical factor in manufacturing components. Any shrinkage in time contributes to a lessening timeline and reduces the effect of non-added values that cannot be suppressed along the value chain. The faster pace to design iterations and on-demand manufacturing with metal L-PBF enhances time savings at the design, manufacturing and use phases. The potential to make quick innovative decisions along the LC can offer financial benefits.

Components needing higher design complexity that cannot or if possible, will require a large amount of energy and start-up materials in CNC machining can be considered for metal L-PBF. Components requiring such complexities which may be non-economic or inefficient with conventional manufacturing methods can be considered for metal L-PBF. Metal L-PBF can be used to manufacture components with high complexity where the part size limit suits the specific limit of the L-PBF machine. Potential metal AM/L-PBF users must be aware that the initial early stages of adoption may generate losses before making profits on their investment.

Certain steps are necessary to successfully adopt metal AM/L-PBF, regardless of the level of entry or mode of application. Companies need to consider the LC benefits that the process offers at the early stage of decision-making, rather than production costs. The energy intensity of metal AM/L-PBF may be amplified or downplayed by the benefits the process offers, depending on the position of users in the value chain. Measures must be taken at the early product design stage by using simulation-driven DfAM to control energy and raw material inefficiencies along the LC of products. Potential process and components failure can be avoided in this way. Measures must be taken to ensure that products are made properly the first time to avoid repeating a build cycle. This helps to eliminate additional cost and time that would otherwise be needed for re-design and re-manufacturing replacement components.

This thesis was conducted based on three objectives (**O1**, **O2**, **O3**) that respectively correlate to three research questions (**R1**, **R2**, **R3**). Qualitative and quantitative methods have been applied to answer the research questions.

O1: Investigate and perform experimental studies to evaluate the factors affecting the sustainability and the circular economy of metal L-PBF. **R1**: How can the factors that affect the environmental aspects of sustainability of metal L-PBF be experimentally evaluated from a life cycle perspective? **Answer to R1**: Metal AM/L-PBF has been shown to be a sustainable manufacturing method from a raw material and energy consumption perspective. The LCI study of input/output resources, products and releases highlighted factors affecting sustainability concerning the environment and the economic dimensions. The LCI study identified impacting factors that could potentially improve material utilisation, energy consumption, scrap metal rate and cost-effectiveness. The identified hotspots (the most impacting factors) were used to understand how they affect environmental and economic aspects of sustainability that would help in making informed decisions. The speculated high energy intensity and production costs of metal AM/L-PBF were identified to be controllable via product design optimisation and with the principles of DfAM. The proper use of simulation-driven DfAM can design and manufacture components that take full advantage of AM/L-PBF. The result of the preliminary review and the LCI study showed that optimising process parameter values offered ways to reduce the highest identified hotspots (high energy consumption) in metal L-PBF. Empirical and theoretical studies of metal AM/L-PBF have demonstrated the possibility of manufacturing components that lessen environmental and economic impacts. The potential of proximity to customer manufacturing can reduce the amount and duration of transportation, thereby minimising CO_2 emissions. Metal AM has the potential to re-design, reduce, reuse, repair, recycle, remanufacture and recover components. Some of the aspects of sustainable manufacturing identified as being achievable with metal AM/L-PBF were (1) localised production offering simplified and reduced supply chains which are otherwise long in CM methods, (2) intricate designs for enhancing product functionality and (3) the ability to recondition and reuse excess powder for new builds.

O2: Create a basic model of an integrated LCC-DfAM model that could highlight the overall benefits of metal L-PBF. **R2**: How does the application of LCC-driven DfAM optimisations in metal L-PBF influence the economic aspects of sustainability from a life cycle perspective? **Answer to R2**: Designing sustainable metal components using simulation methods such as FEA, CFD and generative design has proven to be an effective and efficient way of optimising geometry design, material selection and process parameters that can be used to customise the properties of components. An integrated iterative virtual product design, material selection and manufacturing simulation help to identify and rectify potential defects at an early stage. The application of these digital tools allows a reduction in time on product design, product manufacturing and related post-processing, which translates into cost savings. The DfAM guidelines promote or suppress the use of geometric shapes such as minimum and maximum values of size, inclination angle, allowable bridging distance and other aspects of design for a successful build. The study of DfAM in the design phase has been shown to increase productivity throughout the LC phases of metal L-PBF parts. The high cost of AM systems, high energy consumption and raw material were some of the barriers to utilising metal AM. These challenges can be controlled using digital (design and simulation) tools that allow swift assessment of the buildability with virtual manufacturing before physical printing. This reduces material and energy inefficiencies as no raw material is used. Through a holistic evaluation of electrochemical properties, L-PBF was shown to be capable of manufacturing customised and multi-material metal electrodes to suit specific functionality.

O3: Analyse, modify and verify the created LCC-driven DfAM model of metal L-PBF in the context of industrial engineering and business. **R3**: Which overall model describes LCC-driven DfAM and how is this relevant to the industry? **Answer to R3**: The approaches used in **P1–P5** provided conclusions on how an overall LCC-driven DfAM model was created. A demonstration of how the developed model could be applied to control product design for the required cost-efficacy was verified and validated with an industrial scenario-based case study. Based on the industrial verification and validation, this thesis concluded that the developed LCC-driven DfAM model demonstrated the overall benefits of the entire machine assembly and could therefore serve as a tool for enhancing costs without neglecting functionality. This conclusion promotes the suitability of the developed model to be adopted in further similar studies in AM/L-PBF manufacturing. It is hoped that utilisation of the developed LCC-driven DfAM model will lead to the identification of factors that can be controlled to enhance aspects of sustainability, (environment and economic aspects).

The main conclusions of the benefits of LCC-driven DfAM for industries in achieving sustainable manufacturing designs are:

- Design to reduce production time, waste and emissions
- Design to enhance energy and raw material efficiency
- Design to carter for ease of repair and remanufacturing
- Design to reduce defects or number of production runs
- Design to increase the functionality and efficiency of components
- Design to improve value creation and the longevity of components
- Design to improve LCC from the design, build, use and EOL phases

There is flexibility to control the cost of metal AM/L-PBF using resource-efficient components and batch size control. The exact required number of components can be ordered by end-users without having to commit to minimum order size, as characterised by conventional manufacturing methods. The use of simulation-DfAM to create optimised designs enable cost reductions and reliable components via seamless collaborations between co-design creation and data management of the final components while creating superior products. This is achievable using digital tools and DfAM guidelines to create optimised lightweight designs, thereby reducing raw material, energy and time consumption (see Figure 4.9, Figure 4.10) Best entry decisions can be analysed using both VCA and SWOT models (see appendices P and Q). These strategic tools can inform on how manufacturers can effectively adopt metal AM/L-PBF. Strengthened interrelations between sustainable strategies and business strategies can support the proper implementation of metal AM/L-PBF. The application of sustainable business practices is attainable using simulation-driven DfAM in metal AM/L-PBF. This approach can help optimise the design system to increase productivity and to drive innovations and new research. These are some of the driving forces to using LCC-driven DfAM models. Such a model can help identify the best design optimisation with simulation tools that offer enhanced manufacturing efficiency. This can result in customer satisfaction by offering a swift, cohesive and collaborative relationship between customer demands and design goals.

5.1 The scientific contribution of the study

This thesis was carried out to fill in some of the identified gaps in the literature from existing publications at the start of this study. The results of this thesis were used to identify opportunities to control the environmental and economic inefficiencies of metal L-PBF. Through the studies carried out in this thesis, LCI and LCC analyses were identified as effective tools that can be used to monitor input resources, output products, costs, created waste and emissions. The results of these life cycle thinking tools can be used to identify the positive and weak aspects of manufacturing methods and help in the decision-making process. AM is proven to adequately support the sustainable manufacturing of metal components based on the conclusions of the qualitative and quantitative studies. This thesis created a model of supply chain configuration that highlights the benefits of metal L-PBF (see Figure 4.9). The thesis also identified and determined some aspects of L-PBF that can be optimised to produce metal components of suitable quality while reducing defects, costs and waste.

The results of **P1** and **P2** of this thesis identified ways by which metal L-PBF offers options to achieve efficiencies and reduce waste generation in support of sustainable manufacturing. This is demonstrated by the high utilisation rate of raw material, reduced energy consumption with a combined build, minimal use of process liquids, reduced spare parts stocking and local manufacturing. The disadvantages of L-PBF identified in **P2** were further studied to find a way of overcoming high energy consumption during production. **P3** presents an experimental study to this effect. Experimental-based studies to find the optimised process parameter values shown in **P3** were performed to investigate factors that affect the process phenomena. The relationship between process parameter component quality has been shown to be a possible way of enhancing process efficiencies and decreasing defects in metal L-PBF. This thesis provides a detailed life cycle model that can be utilised to highlight the lifelong benefits of L-PBF. The model shows how simulation-driven DfAM and LCC analysis in **P4** can be used to control costs in the various phases. The results of the DfAM and LCC study show that using the right DFAM guidelines and digital tools was an effective and useful way of enhancing productivity. The model can be used to identify where L-PBF benefits are most achievable. The study in **P5** highlights how L-PBF reduces costs and enhances electrochemical properties such as mass transportation, electrical and thermal properties, with optimised electrode designs.

A final contribution of this thesis is setting the pace for scientific researchers into AM to consider the best adoption strategies in addition to the benefits that the process can provide. This will help potential companies make informed decisions while considering this emerging novel method. This thesis is one of the few, if not the only, to be conducted as a multi-disciplinary approach to mechanical, environmental and business cases. The main contributions of the thesis are illustrated in Figure 5.2.

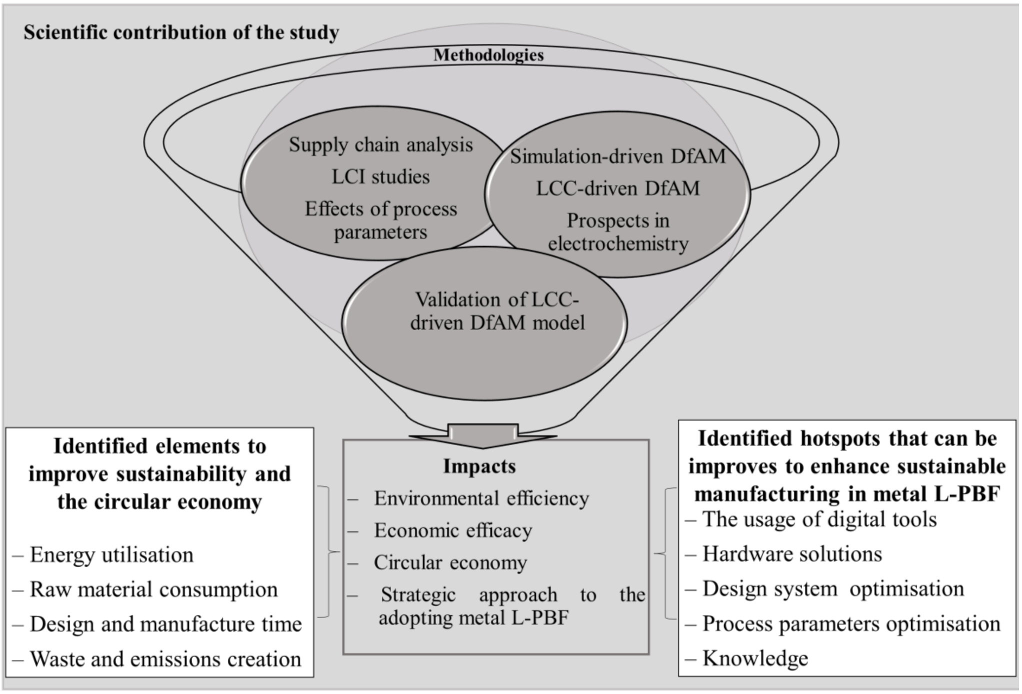


Figure 5.2: Representation of the main scientific contributions of the thesis.

The main contributions of this thesis can be summarised in the form of (1) the proven benefits of promoting sustainability and CE and (2) the developed models that can be used to make informed decisions to the adoption of metal AM/L-PBF. The benefits are as follows:

Proven benefits of promoting sustainability and the circular economy

- Proximity manufacturing with reduced emissions with powder as input is shown in **P1**. This reduces the need for transport and decreases the transportation load, generated waste and emissions thereby reducing the related CF and cost
- Digital and simplified supply chain as shown in **P1**. This has the potential to eliminate physical inventory using digital spare parts and on-demand manufacturing
- Metal L-PBF allows a quick change over of design, enables on-demand manufacturing, offers a digital inventory and reduces the manufacturing cycle, thereby enhancing an agile supply chain

- Metal L-PBF reduces the fuel consumption of dynamic application components during the use phase thereby contributing to CO_2 emissions reductions. Emissions reduction possibilities offered by AM in **P1** and **P2** are presumed based on identified benefits from review and case studies without empirical measurement
- Reduction in the quantity of raw material consumption and the possibility to reuse surplus powder, as shown in **P2**. The use of optimised lightweight component designs and combined build enhance raw material efficiencies
- Flexibility to reduce energy consumption as shown in **P2**. Through combined manufacturing of either similar or dissimilar components, energy consumption, build time and other process auxiliaries (for example shielding gas) can be minimised
- Flexibility to control and vary the quality and properties of the final parts with different process phenomena shown in **P3.** A different selection process parameter values are feasible ways to enhance efficiencies such as increased component quality and decreased defects
- There is flexibility in choosing between several sets of variables (varying or maintaining) and the potential of using pulse lasers to build fine-featured components shown in **P3**
- Better-quality and optimised design components with simulation-driven DfAM, shown in **P4**
- Improve overall LCC through, for example, decreased fuel consumption and number of spare part replacements, warranty and fines at the use and EOL phases shown in **P4**
- Metal L-PBF enhances the performance of electrochemical cell components by increasing and improving their surface area and mass transport properties as shown in **P5**
- Metal L-PBF offers a way to cost-effective manufacturing with optimised and multi-material components, as shown in **P5**

Metal L-PBF is a viable option for redesigning existing components and creating unprecedented optimised and consolidated functional components able to satisfy many of the functionality and performance requirements. Simulation-driven DfAM and the right of selection material, process and hardware solutions can improve overall costs in L-PBF. Metal L-PBF can make lightweight and optimised structures such as lattice-like, tortuous shapes, multi-material components, which offer the possibility of better energy consumption, material efficiency and waste reduction during the manufacturing and use phases as shown in. Metal L-PBF manufacturing can potentially extend the service life of components. Metal L-PBF continue to emerge with the potential to be utilised in other industrial fields apart from the commonly publicised sectors, thereby creating new market opportunities.

Models that can be used to make informed decisions to the adoption of metal AM/L-PBF

The main developed models for supporting the better adoption and effective use of metal AM/L-PBF in this thesis are:

- LCC-driven DfAM model (Figure 4.9) that can be used to enhance product design in order to achieve costs reduction
- Demonstration of how digital tools (see Figure 4.10) can be used to enhance sustainability in metal AM/L-PBF for improved component performance and productivity
- A multi-R approach model to L-PBF (see Figure 4.11) for the potential benefit of the circular economy during the life cycle of components
- A strategic approach to adopting AM/L-PBF (see Appendix R) to achieve enhanced productivity and CSR goals. Identified procedures to apply AM/L-PBF to contribute to SDGs

The industrial relevance of this thesis is the information provided to decision-makers and design engineers regarding how the LCC-driven DfAM model can be combined with strategic business models to make informed decisions in metal AM/L-PBF. Lightweight and intricate design potentially can improve efficiency with the right digital tools, metal powder, processing, hardware solutions and knowledge. Metal L-PBF can flexibly manufacture components of added value without adding to costs with optimised process parameters and designs via digital sustainability. This can be achieved using an integrated system definition process, component design process and manufacturing planning process. The multi-R approach can be applied by industries to enlarge their current working principle which may be limited to the primary 6Rs. This will help to identify targets of circular economy achievable in respective phases and will enable the achievement of the full advantages offered by metal L-PBF towards sustainable manufacturing.

5.2 Further studies

The thesis has shown that metal L-PBF presents new ways of enhancing sustainability and the circular economy (CE) in the manufacturing sector via the performed reviews, case studies, modelling and experimental studies. The results of an LCI study showed that metal AM/L-PBF has a high reusability rate of the surplus powder. The LCI study in this thesis was limited to the manufacturing phase (L-PBF and CNC machining) based on objectives and available funding. Plans to experimentally compare the performance of L-PBF and CNC-machining manufactured components and the effect of build platform utilisation did not materialise due to a lack of funding. Further studies could include experimental analyses of how the planned and other utilisation of the build platform reduce the specific energy consumption in L-PBF. The thesis has shown that the ongoing sustainability studies of metal AM/L-PBF do not include the entire value chain, for example, powder production phases. The sustainability aspects of metal AM/L-PBF must be extended to include the powder production stage to truly reflect its impact on sustainability and the CE. Considering atomisation efficiencies in terms of natural resources, wastes and emissions will give an overall view of the true benefits. The inclusion of the powder production phase will give a holistic view of the environmental impact, thereby avoiding the over/under weighing of the environmental indicators of powder production. The secrecy of powder producers and the task of managing the data quality of all processes can be tedious and costly. This task is considered demanding and extensive and will require some sort of joint effort if it is to be investigated. Academic institutions could partner with industrial sectors in future research on the impact of powder production to redress such gaps in the literature. Assessing the impact to the ecosystem service of metal AM/L-PBF without proper accounts performance at all stages, for example, raw material acquisition and EOL, does not highlight the overall impact of the method on sustainability and the circular economy (CE). The LCA studies could also be extended to include impact assessment and interpretation to enhance the reliability.

The recyclability of unused powder at the production level needs further investigation to support its suitability compared to virgin materials. Excess powders can suffer from contaminants that could affect the required powder characteristics due to exposure to a laser beam. The estimate of a better material utilisation rate in metal AM/L-PBF as shown in the review and this study may be prone to overestimation if industrial and academic research continues to limit the practical studies to the manufacturing phase. Emissions reduction possibility offered by AM is only presumed based on review and case studies without empirical data. Further studies can be carried out to practically measure emission reduction possibilities with metal AM/L-PBF components.

This thesis has shown that process parameter values can be used to optimise the behaviour of the melt pool to control the resolution and quality of components. One way of enhancing the environmental and economic aspects of sustainability of metal L-PBF is by selecting suitable process parameter values that can produce reliable components and reduce the number of build cycles. Measures must be taken to ensure that components are made correctly on the first build cycle to eliminate or decrease the scrap metal rate. The huge number of process parameters that influence the quality of the final component makes the integration of online-control measures almost impossible. This study was limited to studying the effect of five of the most affecting process parameters based on the scope of the study. Further studies on studying the effect of other influential process parameters could provide information for developing intelligent adaptive sensors that could be used to control metal AM/L-PBF during manufacturing.

Based on an experimental study, this thesis proved that the use of simulation-driven DfAM offers a pragmatic means of controlling energy consumption, material usage and costs with complex, simplified and improved performance. The outcome of this thesis showed how costs along the LC can be improved with optimised, better functioning and durable components. An attempt to perform an empirical LCC study was not realised due to a lack of funding. No practical application of this has been conducted in this thesis and a further study of this is required. Further LCC study for selecting design/process alternatives based on the created LCC-driven DfAM model with empirical data is needed to confirm its usability as a decision-making tool to support metal AM/L-PBF adoption.

The thesis highlights the potentials offered by metal L-PBF for sustainable manufacturing. The aspects of sustainability in AM/L-PBF paves the way for new opportunities for a continuous investigation that are not fully understood especially the social aspect of sustainability. Equal accessibility to technologies offers equal opportunities and the ability to customise medical components to satisfy individual biological requirements, collaborate, create jobs are some of the aspects to consider the social benefits of AM/L-PBF. The level of knowledge required to benefit from the social effects of these new research areas and for its continuity is inadequate. Academic institutions could introduce new curriculums in schools/universities and research/industrial sectors as well intensify their current work for scientists, engineers and practitioners to increase the understanding of AM/L- students. This could potentially boost their perception of how AM contributes to creating new fields of studies, collaborations, job creation and to the achieve social aspects of the SDGs.

The thesis showed that the development of new materials, post-processing methods, standard terminologies, certification and validation continue to evolve. One observation during this research was that both academic and industrial institutions continue to use trade names such as SLM™ and DMLS™ in scientific and industrial publications, rather than standardised terminology. This appears to undermine the efforts of standardising bodies. Further studies could focus on publicising some of the harmonising efforts made in AM to achieve the required level of consensus. Continuous use of trade names also makes it difficult to identify the right scientific publications to aid research.

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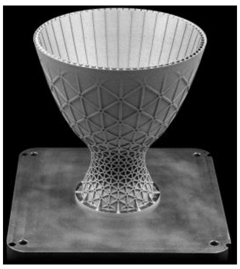
Appendices

Appendix A: Examples of optimised metal components

Examples of unique and optimised components that can be achieved using metal L-PBF are shown in Table 1. The design optimisation was achieved using lattices, hollowed-walls, ribbing and web-like structures.

Table 1: Examples of optimised metal AM components.

Component	Design	Benefits	References
Hierarchical porosity optimisation of Ti-6Al-4V solid-lattice hip prostheses.		• Improved endurance • Faster lead time • Enhance individuality	Courtesy by Altair and EOS. (Burkhalter, 2018)
Lattice optimisation of stainless steel 316L of an integrated internal lattice with hollowed shells of a rocket engine.		• Faster data preparation • Increased functionality	Courtesy by Marten Jurg (Monash University/Betatype, 2017)
Grade 23 titanium rocket nozzle with conformal ribbing.		• Faster manufacturing time • Improved functionality	Courtesy by nTopology and Betatype. (Betatype Ltd, 2020)
Topology optimisation integrated of solid and lattice spider bracket.		• Lightweight • Enhanced strength • Unique design	Courtesy by Altair Materialise and Renishaw. (Materialise, 2018)

(Continued overleaf)

Table 1 continued

Component	Design	Benefits	References
Topology optimisation of a bracket with generative design.		• Faster production • Reduced cost • Better quality	Courtesy by FIT Additive Manufacturing Group. (Fitnik, 2020)

Table 1 shows the different types of optimisation that can be used in metal AM. As can be seen from the figures in Table 1, a component can be designed to have multiple optimisation to improve functioning and aesthetic. The figures depict capabilities offered by metal AM in different fields of application based on combined studies conducted by educational, technical and industrial researchinstitutions.

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Appendix B: Evolution, market trends and fields of application of AM

Appendix B1: Evolution of AM

The industrial sector has constantly evolved with new ideas, methods, tools and materials to produce goods. The continuous evolution includes for example sustainable methods and processes of making goods and services that can decrease negative environmental impacts. The rate of natural resource depletion and climate change are some of the concerns that have necessitated such development. Negative environmental impacts in this thesis refer to the inefficient usage of resources relative to raw material and energy. The trends of AM in relation to the industrial revolution is as shown in Figure 3. (Beyca et al., 2018; Ustundag & Cevikcan, 2018).

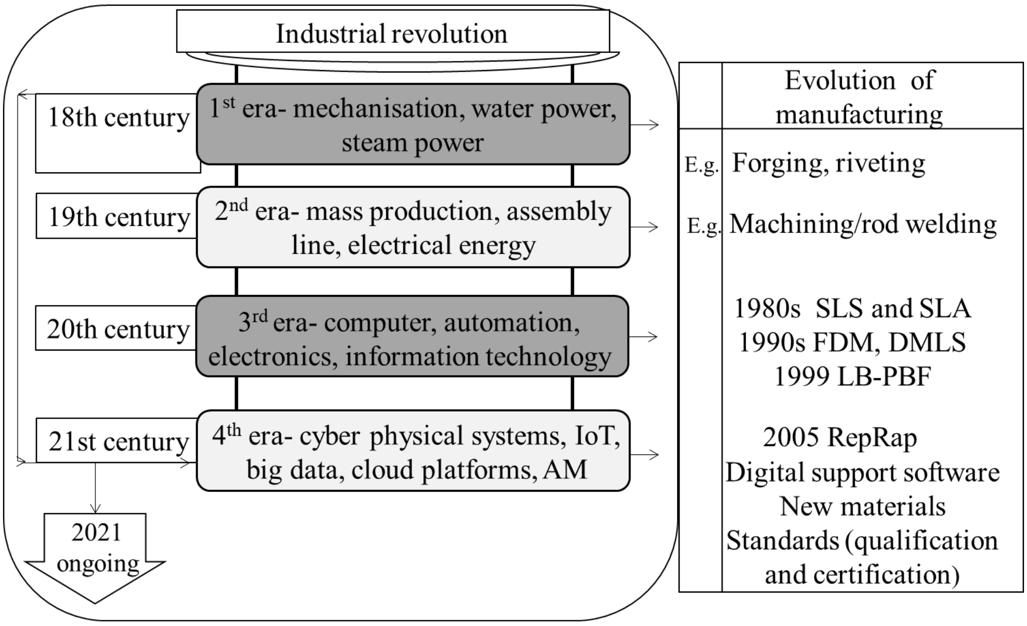

Figure 1: Representation of evolution of manufacturing methods along with different industrial eras with data from (AMPOWER, 2019; Beyca et al., 2018; Chan, 2019; DE Editors, 2010; Duüren, 2016; Gibson & Khorasani, 2019; Jiménez et al., 2019; Miller Welds, 2016; Thompson et al., 2016; Výtisk et al., 2019).

Figure 1 presents some of the important steps of the evolution of AM. The early developmental stages of AM machines were mostly used to manufacture plastic components (Gibson & Khorasani, 2019; Jaster, 2019). As can be seen from Figure 1, the recent trends in AM are in the development of supportive software, new materials and standardisation. These new trends have led to achieving better performing and efficient components with improved productivity (Thompson et al., 2016). The enhancement of productivity is a key driver to increase the uptake of metal AM (Betatype Ltd, 2020) in the industry. The introduction of metal AM has helped industrial fields requiring superior metal components and with better cost-effectiveness (Gibson & Khorasani, 2019). Metal AM refers to the layer-by-layer manufacturing of 3D physical components from digital format using metal materials. Some historical terminologies in the development of AM as can be from Figure 1 are:

- **Selective laser sintering (SLS):** This is a type of AM method, mostly used for plastic materials, that uses laser energy to sinter powder materials. The term was an adopted trade name for an early AM process and technique developed at the University of Texas at Austin by Carl Deckard (Jiménez et al., 2019; Kazmer, 2017)
- **Stereolithography (SLA):** Refers to one of the early AM methods that used patterns of lights, lasers, or radiation to selectively draw and cure liquids layer by layer to form parts. The development of the techniques was led by Charles Hull (Kazmer, 2017)
- **Fused deposition modelling (FDM):** Refers to a form of AM that selectively dispense materials through a nozzle or orifice to print layers of 2D cross-sections to form complex 3D components (Kazmer, 2017). The FDM technique was invented by Scott Crump (Jiménez et al., 2019)
- **Direct metal laser sintering (DMLS):** This is a tradename that refers to an AM method that uses a laser beam to sinter powder materials layer by layer to create parts from sliced CAD models. DMLS was invented by Electrical Optical Systems (EOS) as a rapid prototype manufacturing for components (Stone & Cooper, 2017)
- **Rapid Prototyping and Replication (RepRap):** This refers to an open and freely accessible type of AM that was capable of replicating itself and print objects in plastic based on the principle of FDM to the benefit of everyone. The technology was also referred to as Fused Filament Fabrication (FFF). The initiator of the RepRap initiative was Adrian Bowyer (Jiménez et al., 2019)

Appendix B2: Market trends and fields of application of AM

Wohlers reports (2014; 2016) estimated AM market size to be $20.5 billion and $17 billion USD by 2020 (Wohlers Associates, 2014; Wohlers et al., 2016). The global AM market share based on service and products in 2019 was 11.8 billion USD. The 2020 Wohlers report highlights a continuing growth of AM market and estimates growth of USD 18 billion by 2021, 47.7 billion by 2025 and 117.6 billion by 2029 (Campbell & Bourell, 2020). The globally comparable market size of AM is projected to triple by 2025, from nearly 10 billion USD in 2019 to about 32 million USD in 2025. A furthering quintuple (50 billion) growth is expected in 2029, nearly five times the value in 2019 (Smart Tech Analysis, 2020). The vast difference in the forecasts of these reports could be said to be based on the respective scope of the study. Metal AM is shown to be one of the fast-growing sectors in aerospace, automotive and medicine with unimaginable expansion (Market and Market, 2020; Wohlers & Caffrey, 2013). Market and Market (2020) estimates that the metal AM market will grow at a rate of 32.5% by 2024 in comparison to the value of 2019. Studies have also shown a rapid growth rate of both laser and electron beam-based metal AM (Lee et al., 2017; Wohlers & Caffrey, 2013). This is obvious with the increase in the number of AM machines sold in 2012 (200) and 2019 (2337). The increasing adoption of AM can be attributed to the vast growth in efficiency, aided by the new range of materials, machines, software and standardisation (Gibson & Khorasani, 2019; Thompson et al., 2016). The rationale for using AM differs from sector to sector as expected or derived benefits may differ. Some of the different fields using metal AM to achieve various benefits are shown in Figure 1.

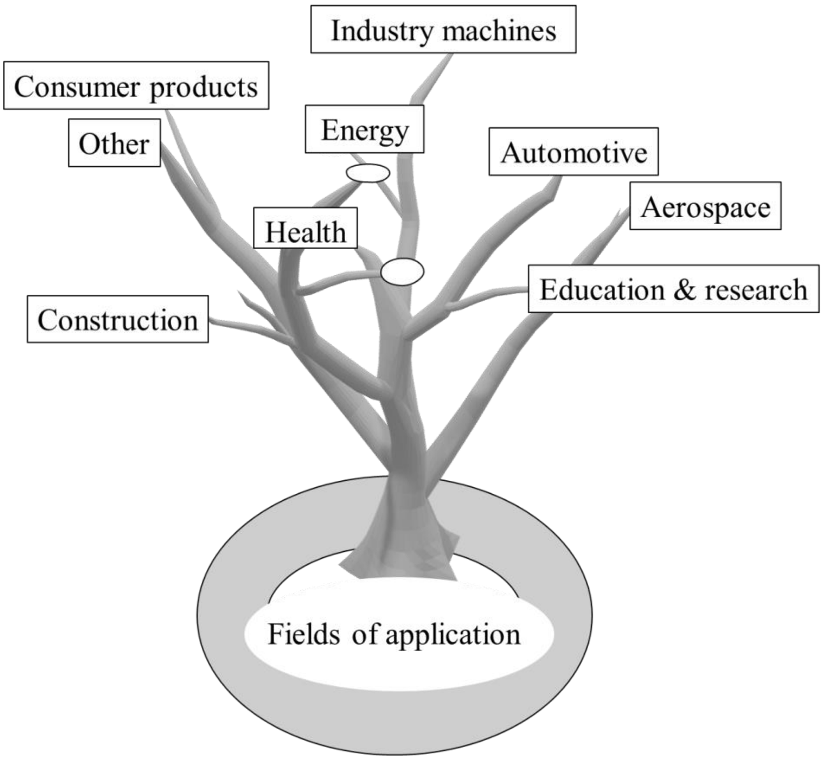

Figure 1: Representation of the major sectors using metal AM (Campbell & Bourell, 2020; Gibson & Khorasani, 2019; Market and Market, 2020; NASA, 2019).

Figure 1 are some of the key sectors using metal AM to achieve benefits numerous benefits (Market and Market, 2020; NASA, 2019). AM technology has matured to become a valuable option to make end-user components that demand stringent mechanical and physical properties, low cycle time and budget (Gibson & Khorasani, 2019; Market and Market, 2020). Bearings are one of such applications which were considered not possible with AM as the process could not be used to achieve the required surface quality to effectively support rotating structures (National Research Council, 2014). Bearings are mechanical elements that permit both rotational and linear movements to be maintained between relative moving bodies by reducing friction between them. Such movements allow effective transfer forces to enhance energy saving (Autonomous Manufacturing Ltd., 2019; NSK Europe, 2020). Current advancements in AM omits geometry constraints making it possible to make cost-effective and lightweight metal gears and bearings components for mechanical applications (Autonomous Manufacturing Ltd., 2019; Jaster, 2019; Plewa, 2019; Saewe et al., 2019). Tailor-made transplant organs, for example, can be printed to suit the genetics of the host bodies (Bose et al., 2018) as this avoids potential tissue rejection. Metal AM allows the printing of biocompatible, multi lattice-solid organs and tissues to enhance mechanical and biological properties. These components are enhanced using varied shapes, forms and with rough surface pores to suit specific genetic requirements (Huckstepp, 2019; Mahmoud & Elbestawi, 2019; Thompson et al., 2016; Wang et al., 2016; Zadpoor & Malda, 2017).

The leading industrial sectors using AM and the growth trends are shown in Figure 2.

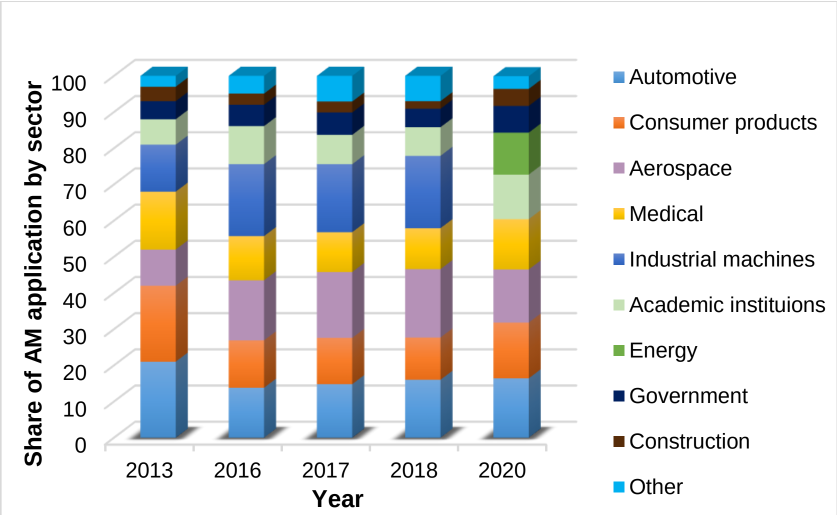

Figure 2: Yearly share of AM application and growth trend (Campbell & Bourell, 2020; Wohlers & Caffrey, 2013; Wohlers et al., 2016, 2018; Wohlers & Campbell, 2017).

As can be seen from Figure 2, AM continues to grow within the various sectors of application and remarkably in aerospace, automotive, consumer goods, industrial machines and medicine. These sectors have remained also main adopters of AM. The 2020 Wohlers report included energy as a new sector of application compared to previous years and also excludes the growth trend of industrial machines. (Campbell & Bourell, 2020).

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Appendix C: Background of sustainable manufacturing

Manufacturing, construction and other industrial activities engage in the indirect burning of fossil fuels using electrical energy generated to produce the raw material used to manufacture products (Fischedick et., 2014; NASA, 2020). This energy usage causes direct (energy-related) and indirect (from generating electricity and heat) emissions during the production of raw material from natural resources (UNEP, 2020). According to CHE, (2017) fossil fuels (coal, natural gas and oil), burning accounted for about 87% of the total human-generated CO_2 in 2017.

Raw material production has been identified as one of the major contributing factors to GHGs (Hertwich, 2019). Hertwich et al. (2019) estimate that one-quarter of global energy is used to produce raw material. Raw material and energy production continues to be essential aspects of manufacturing. However, these processes continue to release waste and emissions into the environment. The material footprint in 2017 compared to that of 2010 indicates around a 12.7 billion ton increase (United Nations, 2020a). Industrial activities accounted for between 21–30% in 2014 and 42% in 2019 of total GHGs (Fischedick et., 2014; UNEP, 2020; US EPA, 2014). Around 44% of CO_2 gases produced in 2014 were generated by the industrial production of materials such as steel, iron and cement (Fischedick et., 2014). Currently, around 47% of CO_2 concentration is generated by human-centred activities (NASA, 2020). There are two ways of addressing rising atmospheric CO_2 (1) reducing emissions and (2) absorbing and storing CO_2. Conscious efforts are needed in order to reduce the industrial human-centric activities that contribute to global warming.

Reducing CO_2 emissions by reducing fossil fuel percentage in the current electricity mix can help reduce indirect energy emissions. Efforts to replace fossil fuels with low carbon sources in electricity production by approximately 98% will help reduce CO_2 emissions from industries (IEA, 2017). Technologies that use cleaner energy sources must be preferred over ones with high emissions generation. Applying such technologies potentially reduces raw material and energy consumption and generated waste. Enhancing material efficiency through better exploitation of natural resources will decrease their scarcity.

The integration of functional materials and additive manufacturing (AM) is a viable means to create high-value components which require lightweight and consolidated designs that are needed to leverage environmental, economic and social sustainability (Chaplais, 2016; Huckstepp, 2019; Simpson, 2020). The integration of augmented reality (AR) systems to AM can monitor and control the production processes that could otherwise not be possible to manufacture (Godina et al., 2020) in real-time and for improved process's reliability and effectiveness (DeSimone, 2015; Godina et al., 2020; Inovar Communications Ltd, 2014). Computer-based simulation software enables to directly design, visualize and verify virtually the structural elements performances under different loading conditions (Barroqueiro et al., 2019; English, 2019; Product Research and Engineering SL, 2020). AI allows the equipment to sense and navigates their environment to communicate effectively and autonomously to perform tasks (Campbell & Bourell, 2020) The use of robots, AI, IoT and simulation to perform routine tasks in modern industries have given rise to energy, materials, cost-effectiveness and swifter decision-making (Microsoft & PricewaterhouseCoopers, 2019). This trend allows manufacturing systems like AM to increase quality, reliability, production speed and to reduce resource consumption, time usage and overall production costs (AMFG, 2018; Motlagh et al., 2020; Silbernagel et al., 2019).

The advancement in sustainability measuring tools has supported the growth in emerging technologies for adequate acceptance. The immaturity of current abilities in AM continues to hinder the adoption of this novel technology as part of mainstream manufacturing. The technological advancement in AM is deemed necessary in areas such as raw material, simulation digital tools, new more efficient machines, hardware solutions, certification and qualification. Extending the lifetime and circularity of components through repair, reusing, remanufacturing, (post-consumer use), recycling and recovery (EOL products) could decrease the energy and raw material required to make new components and raw material.

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Appendix D: Relation between objectives and research questions

Relation between Objective 1, Research question 1 and Publication 1

Publication 1 (**P1**) mainly focused on supply chain and part customisation. A supply chain approach and manufacturing flexibility were used to investigate the environmental aspects of L-PBF and CNC machining. The supply chain approach in this thesis refers to the consideration of assumed metal flow routes that would transform metal, pre-form metal (or powder), into a useable product for the end-user. This included metal preforms, intermediate transportation, manufacturing and finishing processes. The environmental aspect in this thesis refers to measuring the performance and contribution of the comparable manufacturing methods. A schematic of the relation between **O1, R1 and P1** is illustrated in Figure 1.

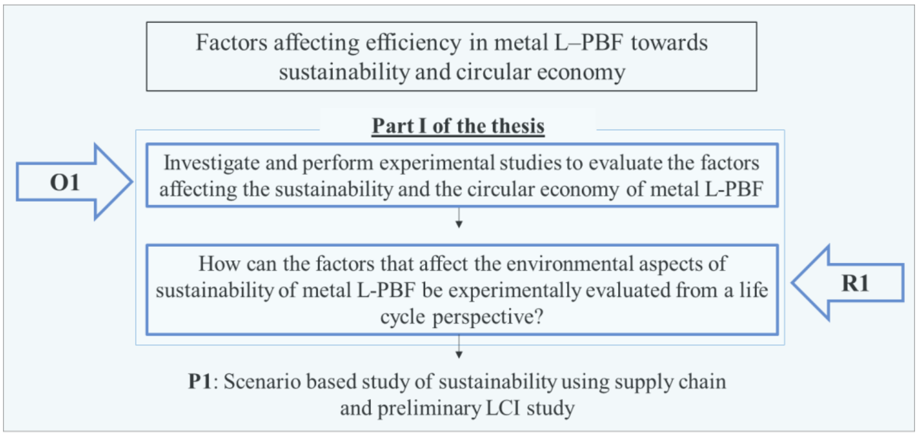

Figure 1: Representation between **O1**, **R1** and **P1** of the thesis.

Figure 1 shows that the first study in Part I of the thesis was based on scenario studies to satisfy **O1** and to answer **R1**. The main finding of this study was publicised in **P1**. The environmental performance of L-PBF and CNC machining were compared in this study. The study created a supply chain model of L-PBF and CNC machining as a methodology to collect data for the LCI study. The supply chain model in this thesis refers to the chain of events that supports the moving of raw material to manufacturing and final components from manufacturing to the end-user via middlemen where applicable. The supply chain models in this study contained people, transportation, materials, technology and equipment. Experimental test pieces based on a varying degree of complexity and shapes geometry were designed to determine the suitability of both L-PBF and CNC machining. The methodologies used in the study were theoretical, scenario modelling and empirical. The study showed that L-PBF can reduce lead time, shorten the supply chain and offer flexibility to make tailored and complex components. Literature review and practical methods were used to show that material and supply chain efficiencies are achievable in discrete metal manufacturing via L-PBF. DED is one of the subcategories of AM that uses thermal energy (laser/electron beam or electric arc) to make parts layer by layer by depositing metal powder or wire via a nozzle.

Relation between Objective 1, Research question 1 and Publication 2

Figure 2 shows the relation of **O1, R1** and **P2** as used in this thesis.

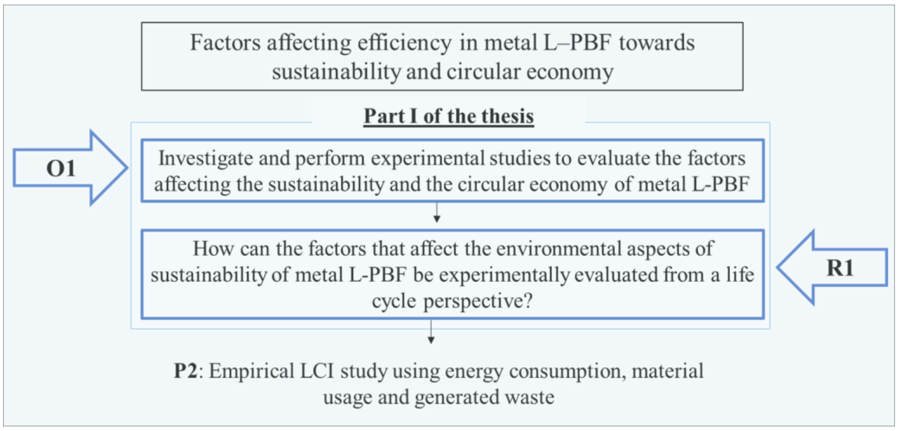

Figure 2: Representation between **O1**, **R1** and **P2** of the thesis.

As can be seen from Figure 2, **P2** was based on empirical studies to answer **R1** and to satisfy **O1**. Practical tests were performed to collect data for LCI analysis. The study showed that L-PBF had a high score in material efficiency of 99% whereas CNC machining tests showed about 75% of mass removed as waste. The specific energy consumption (*SEC*) was quite high in L-PBF than with CNC machining. A disadvantage the benefits of combined build and material saving offered by L-PBF could offset. The extent of modification of the used AM version from the actual industrial machine could practically increase energy consumption. The energy, raw material and related processes aid consumption in L-PBF and CNC machining processes were used to emphasize how both manufacturing methods affect productivity and resource efficiency. Relevant indicators of environmental performance, including measurement techniques for both L-PBF and CNC machining were identified in this study. This study also helped to identify ways to improve energy efficiency in the manufacturing phase.

Relation between Objective 1, Research question 1 and Publication 3

An experimental study of track formation using continuous-wave L-PBF(CW) and pulsed wave L-PBF(P) (in the nanosecond level) was carried out. Different process parameters were selected to control the quality of formed tracks. Process parameters in this thesis refer to processing conditions that could be maintained or changed to control the quality of components during manufacturing. Process condition in this thesis refers to the experience or environment within which an L-PBF machine and component were used. Examples of process parameters used in this study included pulse length, (t_p) layer thickness, scanning speed (V_s), laser power, hatch distance (Δ_{ys}) and volumetric energy density (*VED*). Layer thickness refers to the distance in terms of the height of successive addition of powder material in layer height of each successive addition of material. Scanning speed refers to how fast mirrors of the scanning system can move and how fast the laser beam deflects. Laser power refers to the optical power output of the laser beam, which is either a continuous exposure of the average (peak) power output of CW lasers or pulsation of an exact value. Hatch distance is the distance between successive laser passes. The volumetric energy density refers to the energy input to a material. Pulse length refers to the duration of laser exposure when the pulsation option of scanning is used. Figure 3 shows the relation between **O1**, **R1** and **P3**.

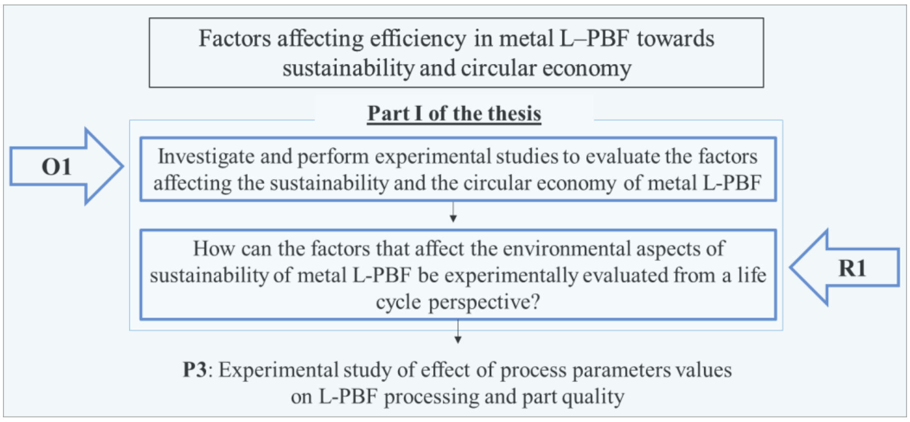

Figure 3: Representation between **O1**, **R1** and **P3** of the thesis.

Figure 3 shows the relation between **R1**, **O1 and P**3 and the study of **Part I** of the thesis. Comparative test pieces were built with L-PBF(CW) and L-PBF(P). The experiment was conducted by varying the pulse repetition rate, scanning speeds and with a constant laser power (20 W) or varied laser power (80, 135, 190 W) respectively for L-PBF(CW) and L-PBF(P). Detailed measurement was carried out in **P3** with numerical values of the selected parameters and their effects on melt pool and scan track quality. The deep numerical experiment was carried out to evaluate the effect of process parameters of L-PPBF. The summary part of the thesis will use the key findings based on L-PBF(CW) and L-PBF(P) to highlight how each can be used to enhance sustainability. The summary part of this thesis generalises the results of the effect of processing parameters. Results of **P3** is used to highlight the impacts of process parameter values to enhancing optimal, efficient manufacturing and potential defects. The deep numerical details are thus not discussed in this thesis because the emphasis in this thesis was to develop an LCC-driven DfAM model. The results of Part I showed that the supply chain, part complexity, component weight, SEC and process parameters in L-PBF influence the environmental aspects. The optimising of the processing parameter values was identified as essential means to enhance quality and resolution. Analysing the product design after **Part I** necessitated the need to investigate the economic aspects of L-PBF. Sustainability cannot be assessed based on only the environmental aspect such as in **P1** and **P2** and **P3** but to consider the entire costs saving along with the life cycle of a metal L-PBF component.

Relation between Objective 2, Research question 2 and Publication 4

The idea of using the right DFAM guideline and digital tools was identified most useful approach to enhance efficiency and productivity. Simulation-driven DfAM and LCC of L-PBF studies were performed to find out from literature the state of the art of simulation-driven DfAM and cost savings along with the life cycle phases of L-PBF. This was the input to **Part II** of the thesis. Identifying the phases of L-PBF were necessary for the best realisation of cost efficiency, productivity and sustainability. Figure 4 shows the relation between **O2**, **R2** and **P4**.

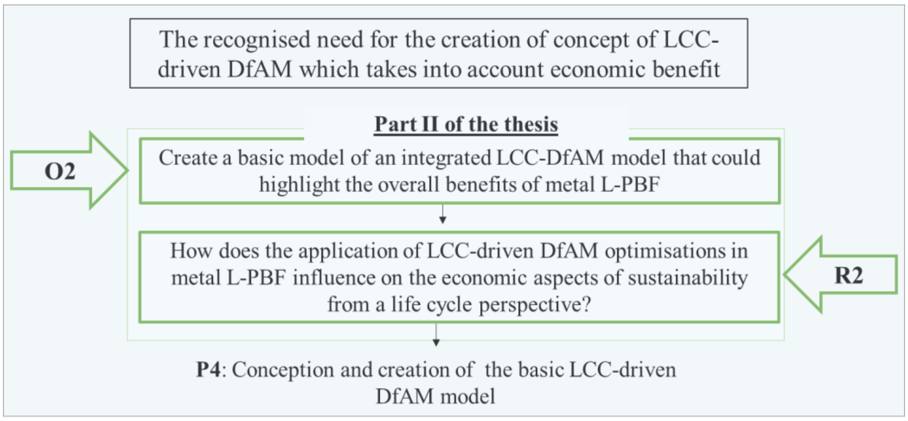

Figure 4: Representation between **O2**, **R2** and **P4** of the thesis.

As can be seen from Figure 4, **P4** was written based on **O2** and **R2** which included a developed LCC-driven DfAM model. The study was carried out as an integrated study of simulation-driven DfAM and LCC of metal L-PBF. Simulation software uses numerical data and CAD designs to virtually model real phenomena in order to predict performance and generate responses to achieve desired objectives. DfAM entails the designing of components in consideration of example size, shape, geometries and materials compositions according to constraints and capabilities of AM. Simulations can be used to discover and create unprecedented components with AM and in consideration of the capabilities of AM. Simulation-driven DfAM refers to the applying of simulations software to design components based on DfAM guidelines and rules. This approach can lead to fulfilling application purposes and other purposes throughout the entire life cycle of components. The earlier study on process parameters in **P3** highlighted the need to investigate how these parameters could be effectively used to control the LCC of L-PBF metal parts. The study in **P4** was carried out based on case studies and simulation modelling. The result of the study showed that controlling the design phase could influence the overall LCC by making optimised parts with few defects which could be tested with virtual manufacturing before physical production. The LCC study showed that the benefit of L-PBF extended beyond the design and build phases to the entire life cycle phases of components. The life cycle phases considered in this thesis were design, manufacture, use and EOL. A simulation-driven DfAM optimised bracket was used with industrial data to show that productivity can be enhanced via integrated DfAM and LCC study. The results of the study were translated into a graphical presentation to generate an integration of the DfAM and LCC (LCC-driven DfAM) model to support the implementation of L-PBF. LCC-driven DfAM entails the designing of components for AM in consideration of current and future cost efficiencies the component will undergo as a single product or as part of an assembly. The efficiencies are generated either as savings in energy usage, raw material utilisation, cycle time or reduced waste and emissions.

Relation between Objective 2, Research question 2 and Publication 5

A review of existing studies provides information on the benefits of L-PBF in the electrochemical engineering sector other than the commonly publicised fields of application. The aim was to promote its acceptance of L-PBF as means to enhance products efficiency in other industrial fields. Electrodes used in separation technology were used as case examples. An electrode can be described as an electron donor (cathode) or as an electron acceptor (anode). The relation between **O2**, **R2** and **P5** are shown in Figure 5.

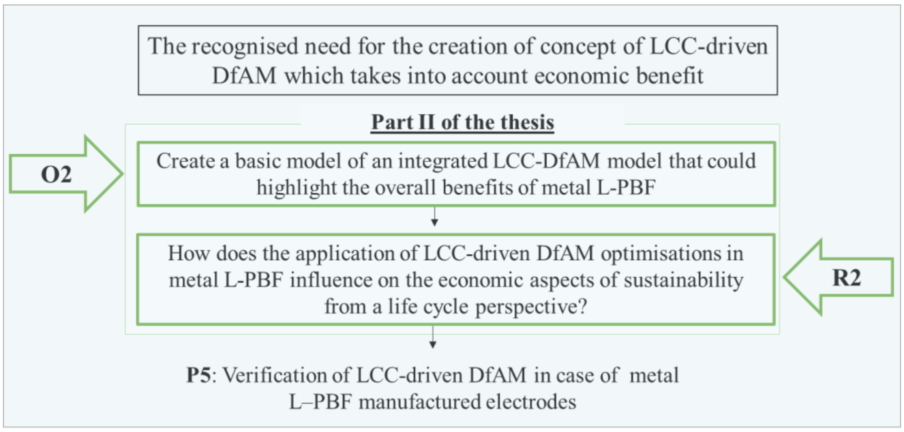

Figure 5: Representation between **O2**, **R2** and **P5** of the thesis.

It can be seen from Figure 5 that the final study of the thesis was performed as a verification of the developed LCC-driven DfAM in metal L-PBF in relation to **O2** and **R2**. The study gave an account of how overall costs, resource efficiency, productivity and sustainability could be enhanced in chemical separation applications. The study highlighted how L-PBF reduces cost and enhances electrochemical properties like mass transportation, electrical and thermal properties, with optimised electrode designs. By a holistic evaluation of electrochemical properties, L-PBF can be used to manufacture tailored metal electrodes to suit specific functionality. Holistic evaluation refers in this thesis to the analysing of required electrical properties with the use of simulation software like computational fluid dynamics (CFD) against the real electrochemical process. An electrochemical process is a chemical process that involves the transfer of electrons often in an aqueous solution via the release of chemical energy or external voltage. Laser-based fusion generates no greenhouse gas emissions and thus has a low environmental impact. Making electrodes for these green applications with L-PBF can enhance for instance performance of electrodes in electrochemical cells and tool electrodes.

<u>Relation between Objective 3, Research question 3 and Publication 1-5</u>

Note that **O3** and **R3** were considered from industrial perspectives as a validation and verification of the modelled LCC-driven DfAM based on the industrial case scenario. The relation of **O3** and **R3** is illustrated in Figure 6.

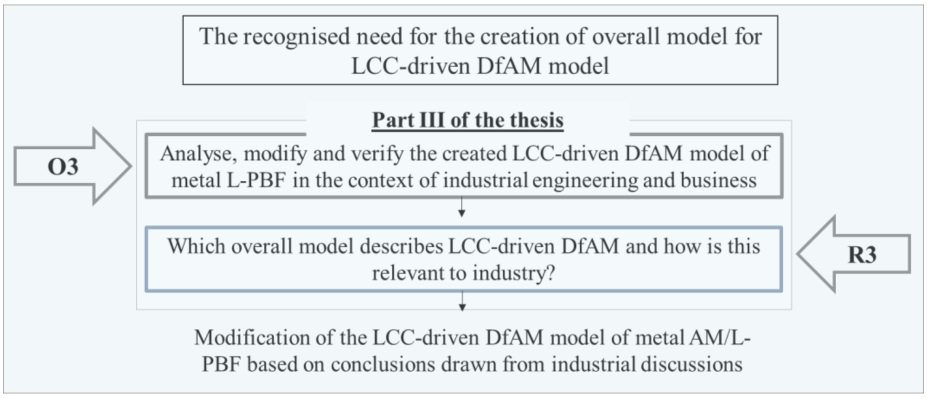

Figure 6: Representation between **O3**, **R3** and **P1**–**P5** of the thesis.

As can be seen from Figure 6, the **Part III** of the thesis forms a summary of **P1**–**P5** and the industrial relevance of the developed LCC-driven model. The discussion was based on the suitability of the outcome of **P1**–**P5** in consideration with a business perspective of the life cycle of L-PBF components.

Appendix E: Metal powder atomisation

Atomisation is the process of forming metal powder by breaking down molten metal with the assistance of high-speed fluid (air, inert gas or water) into metal droplets. The commonly used methods for producing AM metals powders are water atomisation, gas atomisation and plasma atomisation (Dawes et al., 2015; Dietrich *et al.*, 2016; Herzog *et al.*, 2016; Daraban *et al.*, 2019; Inberg *et al.*, 2020; Popov *et al.*, 2021). The AM categories that use powder as feedstock have different requirements for the powder precursor materials (Hryha & Riabov, 2021; Popov *et al.*, 2021) depending on the powder supply and the distribution mechanism during the specific AM processing. ASTM F3049-14 (ASTM, 2014) defines the characteristics which are required of metal powder (feedstock) used for powder-based AM machines. Some of the characteristics are particle size and distribution, morphology, flowability and powder density. ASTM F3049-14 (ASTM, 2014) is a standard guide helping industrial users to make informed decisions and prediction of final components properties based on defined powder properties.

The requirements expected for example L-PBF feedstock include the particle shape (spherical), average particle size (25–55 μm) composition (pre-alloyed or blended), powder flowability (good or high), to mention a few (Hryha & Riabov, 2021; Vock, 2019). The use of powder feedstock with good flow properties ensures a homogeneous spreading and good packing characteristics. The selected atomisation method must be able to produce metal powders that are less prone to oxidising due to the uptake of gases. The potential uptake of oxygen (O_2) by metal powders is one of the challenges which can form oxide layers to the detriment of powder quality (Herzog *et al.*, 2016). Oxide inclusions can negatively affect the flowability, melt pool and subsequently the mechanical properties of final components.

One distinct difference between these three atomisation processes is the form of input raw material and the used fluid (Daraban *et al.*, 2019; Campbell & Bourell, 2020). Water atomisation starts with molten metal, gas atomisation starts with coils, ingots, billets or a mixture (Böckin & Tillman, 2019) and plasma atomisation starts with preformed wires. Water atomisation uses high-pressure water jets to atomise free-falling liquid metals entering an air-filled chamber (Herzog *et al.*, 2016; Kazybek & Perveen, 2019). A common limitation of water atomisation is the irregularity of particle size due to the fast cooling rate (Herzog *et al.*, 2016; Campbell & Bourell, 2020). These challenges make water atomisation a less preferred option for producing powders used in AM despite its low cost.

Plasma atomisation is an emerging method that uses only preformed wires as input (Kazybek & Perveen, 2019). Plasma atomisation uses plasma torches to atomise metals wires into droplets to form powders after solidifying in an inert atmosphere (Kazybek & Perveen, 2019; Campbell & Bourell, 2020). The method with the right optimisation can produce perfectly spherical powders with a variety of particle sizes (Baskoro et al., 2019). The need for pre-formed wire (precursor) before the plasma atomisation process can increase cost and this also means that metals that can be formed into a wire can be processed with this process (Kazybek & Perveen, 2019; Campbell & Bourell, 2020).

Gas atomisation uses pressurized gas to atomise or to break free-falling liquid metals into droplets entering an atomiser from a vacuum or inert filled chamber. The droplets of metals solidify into spheroids in the cooling chamber and fall into the collecting chamber (Dawes et al. 2015; Precision Metalforming Association, 2017). Gas atomisation can produce powder of varying particle size to up to 300 µm (Hryha & Riabov, 2021). The final stage involves sieving of the produced metal powder into specified particle size classification. Using inert gas like argon (Ar) in the gas atomisation route omits/reduces the uptake of O_2 thereby reduce forming of oxide layers (Dietrich *et al.*, 2016).

Gas atomisation and plasma atomisation processes are preferred options to make AM metal powder as the required particle size and shape for AM are achievable via these methods (Herzog *et al.*, 2016; Aboulkhair *et al.*, 2019; Kazybek & Perveen, 2019; Campbell & Bourell, 2020). Gas and plasma atomisation can produce spherical shaped and uniform particles size of good flowability and uniform powder bed. The gas atomisation is advantaged over plasma atomisation it does not require pre-forming of input material as required in the plasma atomisation. This makes gas atomisation a preferred option in terms of cost to the plasma atomisation. The schematic of gas atomisation is shown in Figure 1.

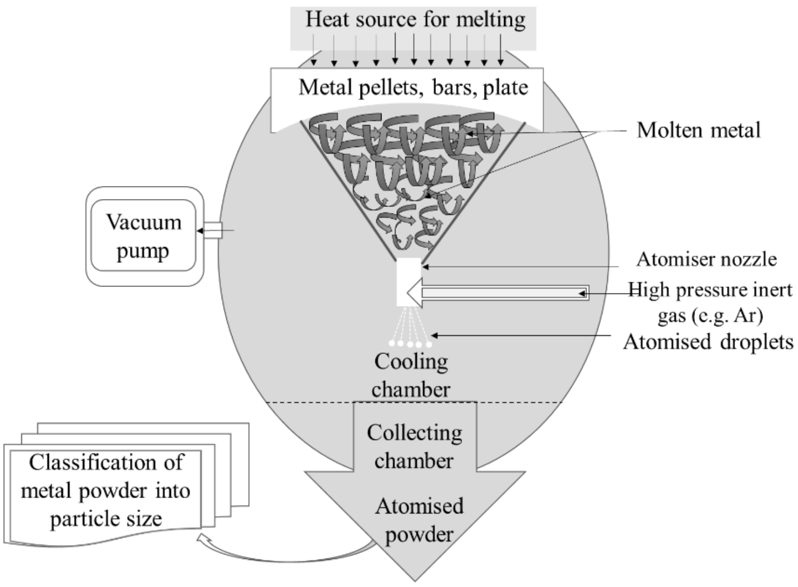

Figure 1: Schematic diagram of gas atomisation processing layout of metal material, Redrawn from (Eckart, 2020; Hryha & Riabov, 2021; Stone & Cooper, 2017; Zheng *et al.*, 2009).

Figure 1shows the process flow of gas atomisation which starts with the heating up of elemental bars, plates, billet or their combination. An inert gas (for example Ar) at high pressure is sprayed at the falling off liquidised metals to form atomise droplets in a chamber.

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Appendix F: Supplementary sheet structure of the study and thesis overview

Part I: The recognised need for research and development in the sustainability of L-PBF for metal components.

The acceptance of L-PBF was anticipated to increase with scientific studies that would investigate and identify the suitability of the process as an enabler of sustainability. The review highlighted well the benefits yet there were hindrances to metal AM becoming part of mainstream manufacturing. This was debated from the viewpoint of the high initial capital investment (machine, powder, labour) and high energy consumption during production. The sequence of activities to answer Research 1 **(R1)** based on Objective 1 **(O1)** is illustrated in Figure 1.

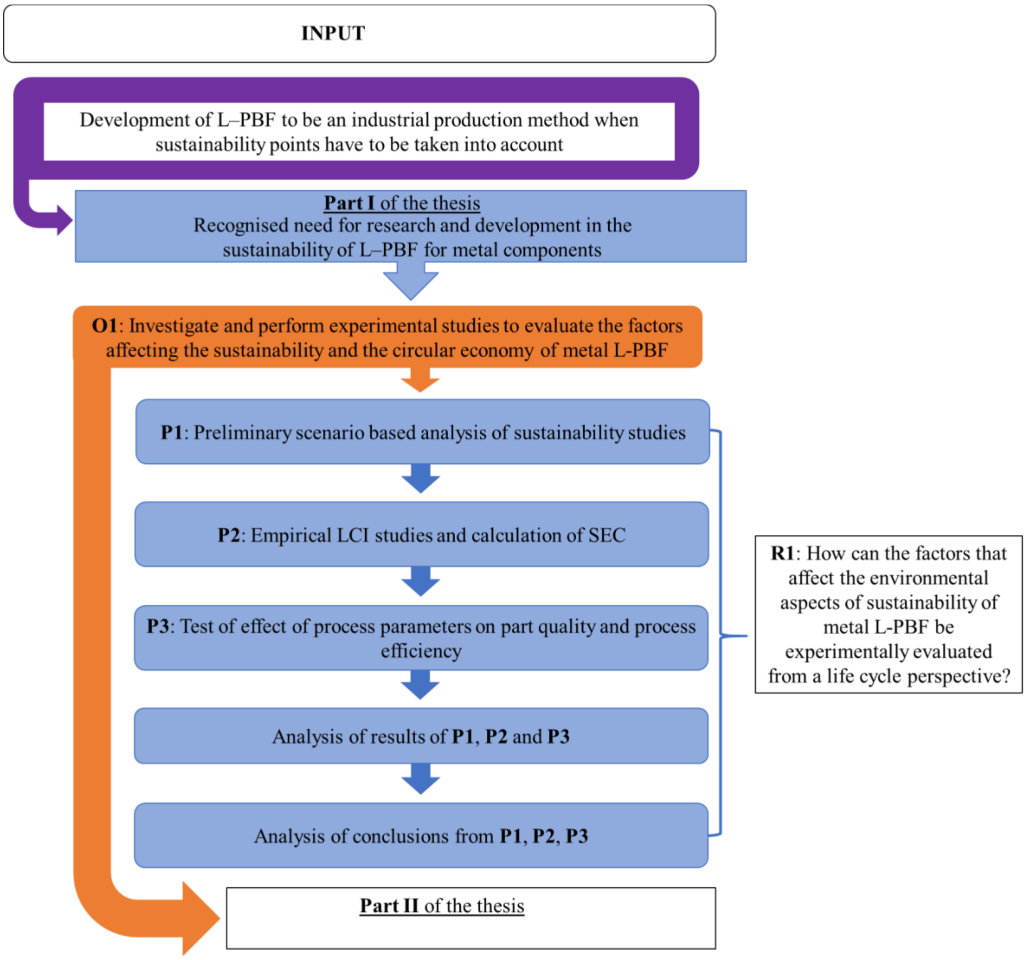

Figure 1: A representation of the detailed structure **Part I** to answering research question 1.

As can be seen in Figure 1 the **Part I** of the study included the LCI study which was used to systematically inventories input and output of material, energy, processes fluids and time. Further study on process parameters was performed to find optimised process parameter values to control part resolution. Preliminary review results showed that optimising process parameter values offered ways to reduce identified hotspots (high energy consumption) in L-PBF. Analysis and conclusion of **Part I** showed L-PBF offered advantages beyond production which could offset the limitation of high process energy. Simulation-driven DfAM was identified as one way to optimised product design to control overall costs and energy.

Part II: The recognised need for the LCC-driven DfAM model.

Part II was based on the recognised need for the creation of the concept of LCC-driven DfAM which is considered an economic benefit. There were identified gaps in the literature on the totality of benefits metal L-PBF offered along the entire life cycle of components. The evaluation of the overall costs and environmental benefits of L-PBF was necessary evaluated using data from the pieces of literature, on costs, raw material and energy consumption. The sequence of stages to answer **R2** based on **O2** is illustrated in Figure 2.

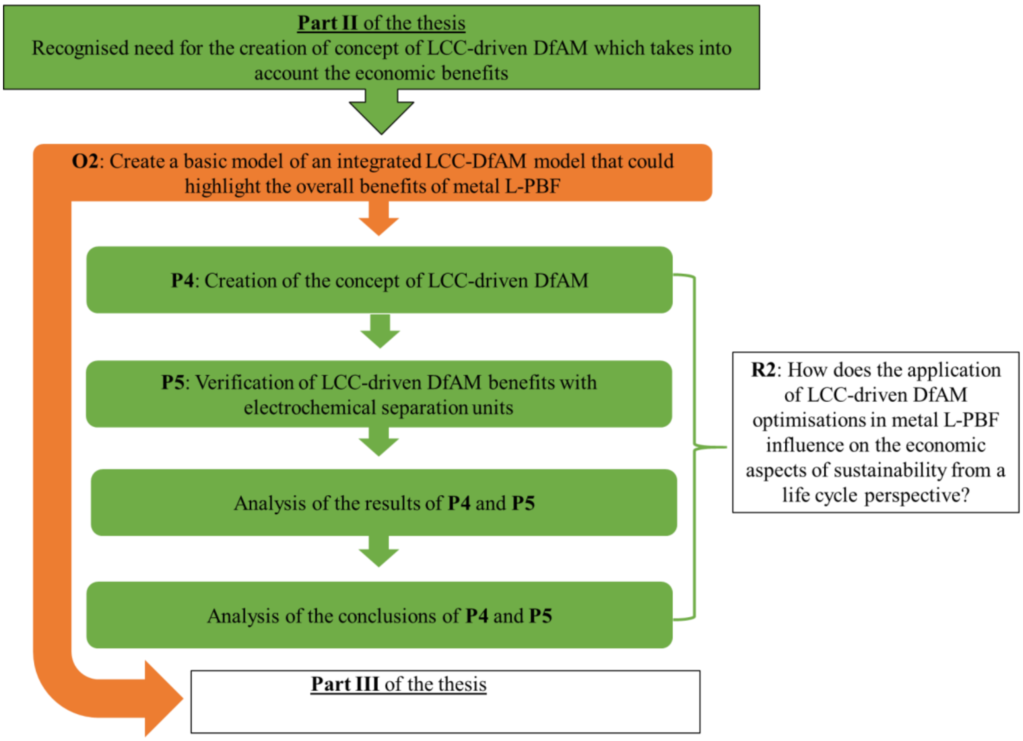

Figure 2: A representation of the detailed structure Part II to answering research question 2.

As Figure shows, **Part II** of the study concentrated on DfAM and LCC. The influence of DfAM on metal L-PBF was highlighted with data collected from the literature. The benefit of optimised designs through simulation-driven DfAM was identified to offer unprecedented new ways to create effective, better and improved performing components for industrial application. Metal L-PBF offered resource efficiencies by reducing manufacturing time and steps therefore energy consumption and cost. The analysis and conclusions of Part II were modelled to an LCC-driven DfAM in **P4**. The model presented a preliminary economic benefit of metal L-PBF throughout the lifetime of components Further validation and verification were required of the developed LCC-driven DfAM model to suit industrial relevance and this formed the basis of **Part III**.

<u>Part III: The recognised need for an overall industrial relevant LCC-driven DfAM.</u>

Part III has its origin in the recognised need for the creation of an overall model for LCC-driven DfAM. This part was done in collaboration with an expert from the industrial sector. The goal was to evaluate the practicality of the developed LCC-driven DfAM model from an industrial perspective. The sequence of stages to answer **R3** based on **O3** is illustrated in Figure 3.

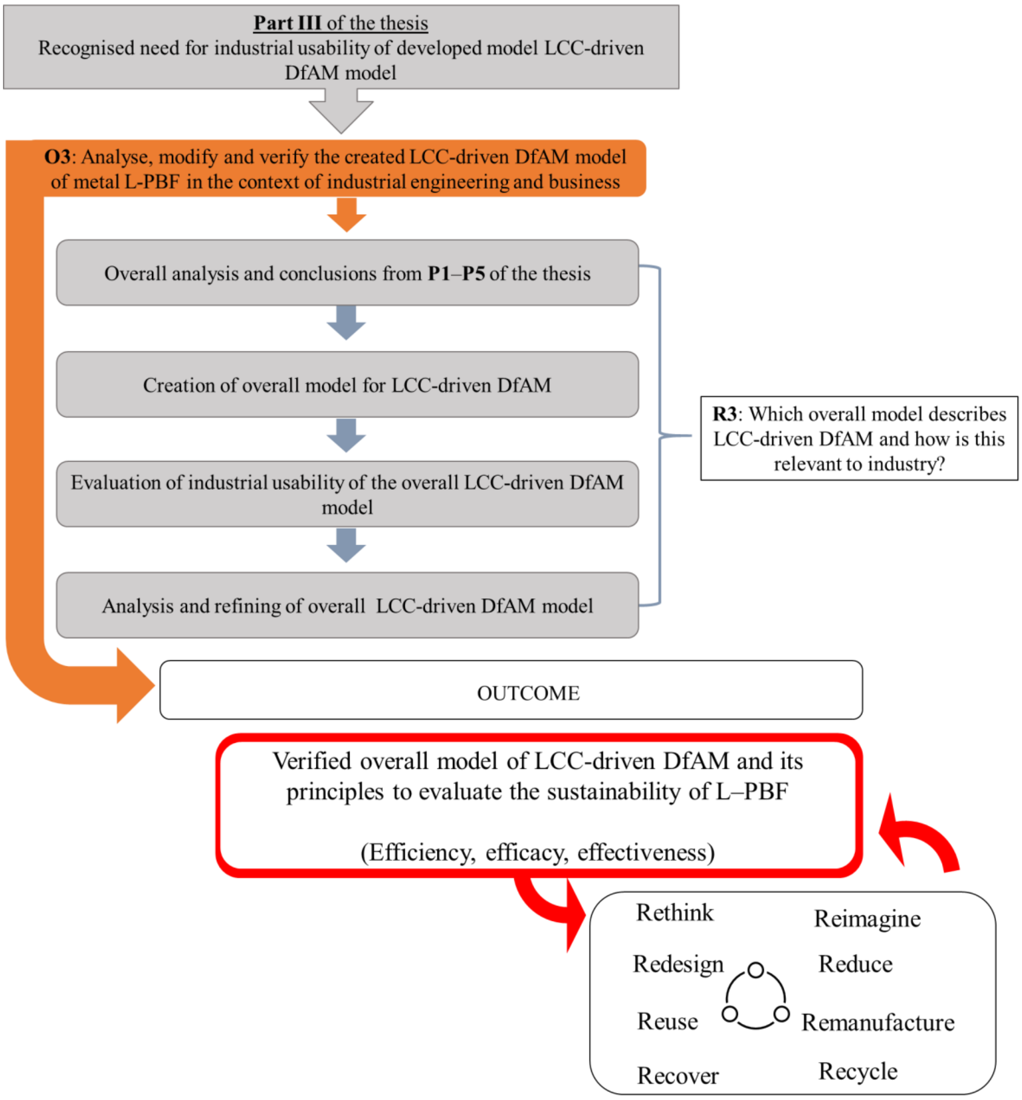

Figure 3: A representation of the detailed structure **Part III** to answering research question 3.

Part III of the thesis as can be seen from Figure 3 included the validation and verification of the developed LCC-driven DfAM model based on industrial context. A pragmatic step by step discussion was used to appraise the modelled LCC-driven DfAM model in **P4** and this resulted to further modification. Evaluating the industrial relevance of the model introduced business models ideas such as value chain and SWOT analyses. These analyses were needed to make specific cases under which the model would be regarded relevant and from which stages industries will realise benefits.

Appendix G: Notions of sustainability and the circular economy

Figure 1 represents the core components of sustainability and the two perspectives of sustainability Figure 1b,1c.

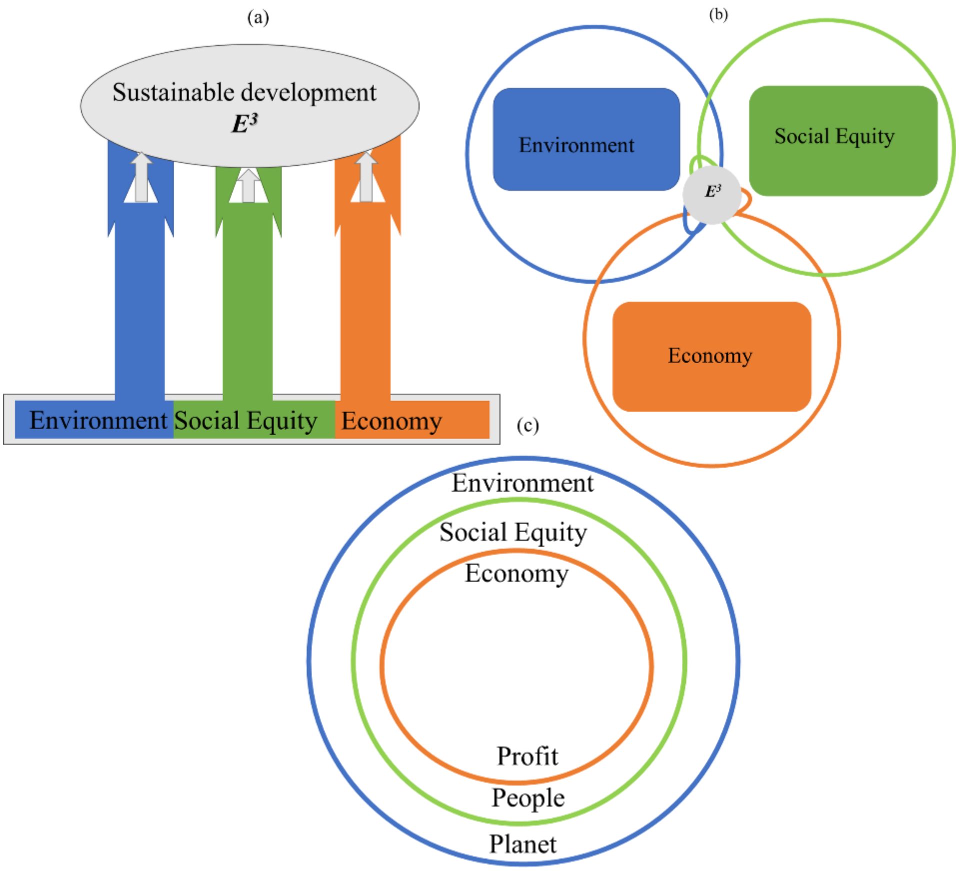

Figure 1: Representation of the (a) three core pillars (b) intersecting classical model and (c) contemporary concentric model of sustainability (Eizenberg & Jabareen, 2017; Purvis et al., 2019; Yolles, 2018).

The growth in sustainable developments can be ascribed to legislative regulation and self-set corporate responsibility (CR) targets. The driving forces to the increased efforts towards circularity are the increased awareness about environmental and social issues of the customers and inhabitants of societies within which companies operate. The use of the CE can potentially maximise value creation (Bhattacharya et al., 2011) and this should be perceived from all the three dimensions of sustainability, i.e., economic values, environmental values and social values (Brozović et al., 2020; de Brito & Terzieva, 2016; Jaeger-Erben et al., 2021). The CE is criticised to be centred on the ecology and economic aspects of sustainability. Circular society (CS) aims to reframe CE to go beyond growth, technology and market-based solutions to include social policy measures (Jaeger-Erben et al., 2021). Such extension offers companies an additional tool to succeed in a competitive market (Impact Garden, 2020).

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Appendix H: Quality assurance in metal AM

AM, unlike conventional manufacturing methods, does not allow the simple sampling of comparable components manufactured under the same conditions and with the same materials to represent a batch size (DNV GL AS, 2017). The geometry of printed parts has an enormous effect on this because the heat has to escape somewhere from the melt pool and the only way for heat to escape is through printed parts. The more different geometry is the more different the final metallurgical structure of the component is. The metallurgical microstructure of printed components is unique for each geometry in L-PBF. There can be variance in regions of different layers of the same component produced with L-PBF. The vast variance of processing parameters and properties of feedstock can influence the reliability and quality of final products (Foster et al., 2020). Efforts have been made to simplify the aspects that are worth considering in ensuring AM parts fulfil required functionality and performance. There is no all-inclusive standardised method to ensure metal AM components satisfy essential the requirement or quality.

The qualification of metal AM can be tackled from (1) technical requirements, (2) repeatability and (3) consistency (DNV GL AS, 2017; Sigma Labs Inc., 2020). Technical requirements evaluate the feasibility of the resultant part to satisfy technical requirements, for instance, structural and thermal analysis. Repeatability evaluates the practicality to produce the same result over time for different batches. Consistency evaluates the possibility to track the history of the component within the boundary of the design and manufacturing stage of a life cycle. General AM standardised qualification and certification continue to evolve to suit metal AM (Monzón et al., 2014; Seifi et al., 2016). Few standards including ISO/ASTM 52910 (2018) and ISO/ASTM 52942 (2020) are applicable to metal L-PBF. There is anticipation for more metal AM specific standards to evolve. Potential qualifications under development include ISO/ASTM AWI 52935, ISO/ASTM CD TS 52930 and ISO/ASTM CD 52920 (ISO, 2021; ISO/ASTM, 2020a, 2020b). Emerging standards such as ISO/ASTM AWI 52935 and ISO/ASTM CD TS 52930 (ISO, 2021; ISO/ASTM 2020a; 2020b) are tailored to suit the role of AM in SDGs. These standards aim to ensure that components, materials, processes of AM are not only meeting technical, reliability and repeatability aspects but also meeting targets of SDGs goals 4 and 9 (ISO/ASTM, 2020a; 2020b).

The advancement in AM standardisation has led to the development of testing methods. These tests can be used to monitor, analyse and qualify the build process and finished components (Chaplais, 2016; DNV GL AS, 2017; EOS 2020; Sigma Labs Inc.z, 2020; VELO3D, 2019). Qualification and certification are both required to ensure the quality and reliability of metal AM components (NASA, 2019). The qualification aims to monitor and control the design, material and process during the development or testing phase to determine whether specific requirements are fulfilled. It focuses on technology and manufacturing procedure. The available tests for AM may be destructive tests (DT) and non-destructive tests (NDT). Available NDT methods include X-radiation (X-ray), computed tomography (CT), optical tomography (OT), laser ultrasonic testing (LUT), Eddy current testing (EC) and neutron diffraction (ND) (DNV GL AS, 2017; EOS, 2020;

Hinebaugh, 2018; Sigma Labs Inc., 2020; NASA, 2019). Quality assurance (QA) of the input powder is performed before the build process to ensure feedstocks are free of, for example, inclusions that may affect the reliability of final components. NDT such as X-ray and CT can be used to characterise inclusion to ensure the reliability of finished components (Hinebaugh, 2018; NASA, 2019). Certification aims to evaluate material and products during or after final production against the technical requirement. Certification focuses on material and product assessment (DNV GL AS, 2017; NASA, 2019). Different NDT (for example, X-Ray CT (XCT), EC, ND) and DT (for example compression test, fatigue bending test) can be used to evaluate and certify the quality of final components. (DNV GL AS, 2017). ND and XCT/CT are examples of effective tests for assessing the quality of manufactured products. ND and XCT can investigate for example materials reliability, bulk properties to a microscopic structure. These tests can identify localised induced residual stresses and porosity in manufactured components. The tests are versatile and powerful analysis tools that can be used to evaluate the internal stress and porosity of an in-situ or the actual sized components. Identifying such defects against simulated scenarios can offer a better understanding of failures and their causes. Finding such root cause relations can help optimise the process parameters to control voids, defects, uptake of inclusion or part failure.

QA can be measured and monitored for the system, material and process parameters in recent times before and during the manufacturing phase and after successful manufacturing. Both online monitoring systems and offline computational based simulation (Seifi et al., 2016) can be used for such purposes. There are different process monitoring such as as (1) the oxygen content of the chamber and (2) the build process, which is performed to ensure quality and successful components are manufactured free of post-manufacturing voids. Monitoring systems use either (1) camera-based or (2) sensor-based to communicate and check the internal structure of the components. An automated sensor for halting the build process at detection of any undesirable condition is integrated. Some of the existing software that allows the checking of component quality include ANSYS, EOSTATE ExposureOT and Sigma Lab's IPQA™ (ANSYS, 2017; EOS 2020; Sigma Labs Inc., 2020). The advantages of in-process monitoring include cost and time savings as operators can monitor defects (Thomas-Seale et al., 2018) in real-time. There is no doubt energy and materials efficiencies will be enhanced in L-PBF with an automated process interruption, as few defaulted components will be manufactured. This approach is not entirely time and cost-effective and can cause a delay in production. There is the need to have in-process adaptive control systems. In-process controlling systems are systems that can give adaptive feedback to the machine on what could be done to rectify a detected problem. This ensures a continuous process without stopping the process as this can omit potential manufacturing downtime. The goal would be to develop a kind of closed-loop process control system. Closed-loop is defined as '*an automatic control system in which an operation, process, or mechanism is regulated by feedback*' (Merriam-Webster, 2021). A key limiting factor to hindering such a closed-loop is that metal AM has too many parameters affecting the process plus the complexity of component geometry. This could complicate the possibility to have one controlling closed-loop system.

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Appendix I: Process parameters optimisation

The use of metal AM/L-PBF inherently is controlled by several parameters (Hansen, 2015; Ituarte et al., 2015; Piili et al., 2018) and this sometimes makes the finding of the optimal settings a bit challenging and hectic. Different process parameters can create various process conditions which can influence the properties and quality of final components. Selecting suitable parameters is needed to ensure reliable and durable components are produced. The determining of effective process parameters in metal AM can help produce high-end components (Leirmo & Martinsen, 2019; Yadroitsev et al., 2015) to fulfil required standards, integrity, functionality and to reduce cost and energy inefficiencies. Digital simulation tools can be used to quicken the finding of reliable process parameters. Metal L-PBF in simple terms is a microscale laser welding (Ranjan et al., 2020) of metallic powder that creates a laser beam/powder interaction to form a melt pool as demonstrated in Figure 1.

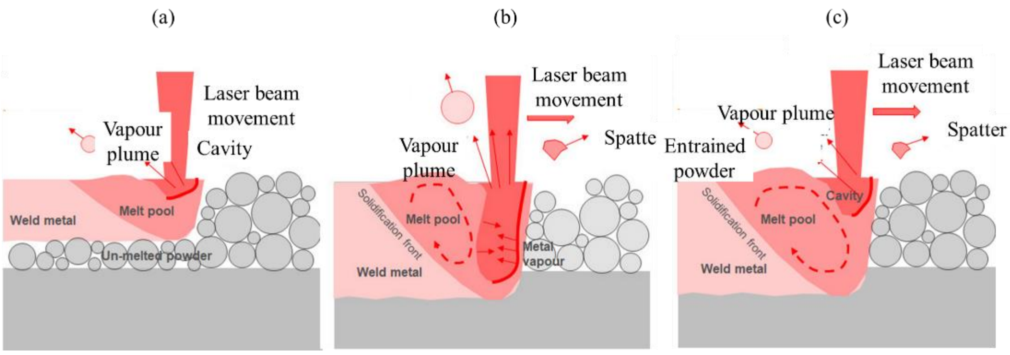

Figure 1: Representation of melt pool modes (a) insufficient penetration (b) keyhole effect and (c) efficient conduction mode in L-PBF (Saunders, 2017).

As can be seen from Figure 1 the laser power controls melt pool depth and the penetration effect in L-PBF (Saunders, 2017). The input of too small laser energy reduces the penetration of the melt pool (see Figure 1a) thereby causing incomplete fusion between the metal powder layer and the top surface beneath the solid metal. The effect of having an unmelted powder between the layers are porosity and delamination (Molitch-Hou, M. 2017). The presence of spatters on surfaces and part delaminating from the build plate can cause a collapsing of the process during the recoating process. The build chamber requires usually inert gases to create a shielding effect for the materials against oxidation (Fedina et al., 2021; Gunenthiram et al., 2018).

The input of too-small power for a given speed can result in insufficient melt pool depth required to reach the previously formed molten layers to adequately conduct heat away. Exposing metal powder to a high laser power value at a given speed creates a keyhole effect (see Figure 1b) in the optimal area of the micro-scale instead of a preferred conduction welding (Hansen, 2015; Patel & Vlasea, 2020). The exposing of laser can be continuous L-PBF(CW) or pulsed L-PBF(P) (Saunders, 2017) depending on design goal. A keyhole is an empty area formed by metal vapour from the front of the beam as a result of high input heat and this can cause materials to vaporise. The evaporation process inside the keyhole determines the amount of the vapour plume (Brock et al., 2014). The effect of deep keyholes welding is the tendency to create an unstable melt pool, poor formation of already formed layers and spattering. This can cause bending, boiling, burning, cutting or evaporation of the materials which can result in overheating and poorly formed tracks (Hansen, 2015; Laitinen et al., 2019; Yadroitsev et al., 2015).

The basic principle in L-PBF is to stabilise between phases of lack of fusion (see Figure 1a) and deep keyhole (see Figure 1b) to achieve the desired option (Refer to Figure 1c). Numerical simulation-based analysis can be used to select suitable values, to predict melt pool behaviour and causes of possible overheating before the actual build (Ranjan et al., 2020; Yadroitsava et al., 2015). This aspect of design optimising is necessary to avoid several temperature-related defects. The input of laser power of 190 W means high energy density is concentrated powder bed of uniform 50 µm layered powder. The input of such high laser intensity theoretically can cause increased spattering, deepen keyholes and even cutting through components.

Data from literature indicated that process parameters that are mostly optimised to control the build process include laser power, layer thickness, hatch distance pulse length and scanning strategies (Buchbinder et al., 2011; Hansen, 2015; Kok et al., 2018; Wei et al., 2021; Yadroitsev et al., 2013). Certain process parameters (for example, pulse length, peak energy, frequency) needs to be considered when the pulsation option is used. Figure 2 illustrates the commonly studied parameters that can be optimised to control the manufacturing processing in L-PBF (Hansen, 2015; Yadroitsev et al., 2015).

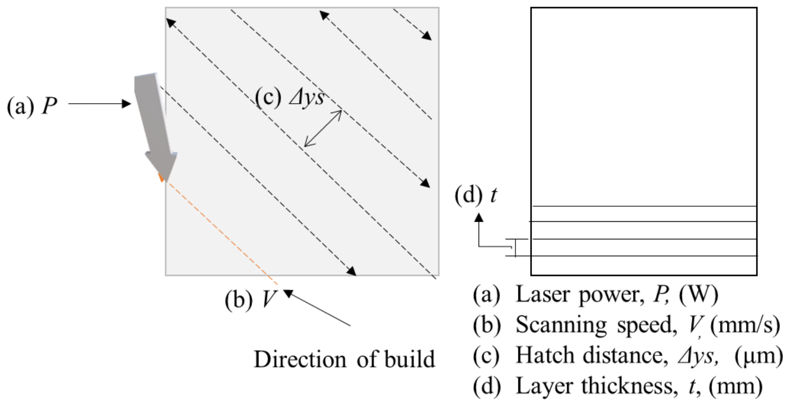

Figure 2: Illustration of some process parameters of L-PBF.

The demonstrated process parameters in Figure 2 are identified based on data from the literature as examples of mostly influencing process parameters to the component features and functioning of finished metallic components (Buchbinder et al., 2011; Hansen, 2015; Kok et al., 2018; Wei et al., 2021; Yadroitsev et al., 2013). Parameters such as laser wavelength, laser power, scanning speed, scan paths and powder characteristics greatly influence the resulting component properties such as surface quality or part density (Alsalla et al., 2018; Cherry et al., 2014; Hansen, 2015; Oliveira et al., 2020; Rashid et al., 2017; Saewe et al., 2019; Yadroitsev et al., 2015). Scanning speed is among the easily changeable process parameter in L-PBF. Studies have shown that varying the scanning speed for optimal value with fixed adequate layer thickness can result in the formation of stable tracks (Laitinen et al., 2019; Yadroitsev et al., 2015). Using the unsuitable scanning speed values to laser power can affect the stability of the melt pool and create beading effects. Finding the optimal speed and laser power can increase process speed. The limits of how fast laser beams move and how high power a material can withstand must be considered to avoid unstable melt pool behaviour.

The right combination of scanning speed and laser power can form a stable melt pool to attain the right mode of conduction (Hansen, 2015; Saunders, 2017). Optimal processing with L-PBF can be achieved by having enough power in a single spot, irrespective of the type of laser exposure L-PBF(CW) or L-PBF(P). The input energy must be sufficient to create a deep enough melt pool that can melt materials in front, in a stable condition and connects to previous layers so that heat can escape. Note that the conductivity of a material is another contributing factor to heat transfer in L-PBF.

The scan strategy has the potential to impact characteristics such as residual stress, microstructure and surface quality of manufactured components (Ali et al., 2018; Yadroitsev et al., 2015). The selection of a scanning strategy must be done to avoid any defects that might result in undesirable features to eliminate the need for extra post-processing and cost (Ali et al., 2018). Scan patterns define the scanning path of part contours within an area in direction of the x-y-axis. Different configurations of scan patterns are stripe, checkerboard and islands pattern and these can be used singly or as a combination to control a process. Scanning strategy refers to the type of scan pattern, the number of counts and the allocation of laser parameters to a specific area in the scanning of a layer. Different optimising with altered scanning strategies and other process parameters can be used for different sections of components to enhance density and surface quality. The presence of gaps between scan tracks can cause chains of pores in the final components (Yadroitsev et al., 2015).

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Appendix J: Comparison of CM and AM methods

Conventional manufacturing continues to be a useful and irreplaceable method to make products. Conventional methods include manufacturing methods that make products through (1) removal of material, (2) forming of material, (3) joining of material and others (Abdulhameed et al., 2019; Zhu et al., 2013). Industrial evolution has remained constant and as companies continue to grow in knowledge and expertise, new ways and methods to enhance the efficiency of the existing component or to create new efficient components continue to expand. One of the notable reasons why efficient methods and processes are growing constantly is the undesirable impact on the ecosystem from manufacturing and production systems (Microsoft & PricewaterhouseCoopers, 2019). Conventional methods such as machining are characterised by the purposeful removal of materials that are later recycled. Such actions cause unsustainable use of resources such as natural ore, energy and process aid. Machining methods use billet (sheet, plate, bar, tube), larger than final part, as start-up materials (Pannett, 2019). L-PBF can be said to be the preferred option to machining metal components where replaceable as material saving is high with the layerwise manufacturing of powder materials.

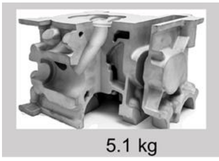
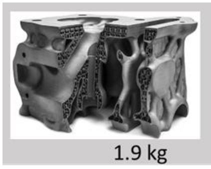
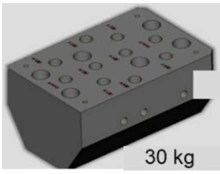
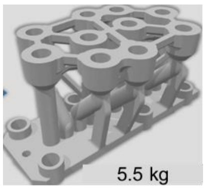
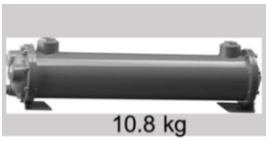
The adoption of AM must be planned and executed to derive maximum benefits offered by the process (Seifi et al., 2016). AM complements existing conventional manufacturing methods (Gibson & Khorasani, 2019; Tofail et al., 2018) and some of the conditions where the former will suitably replace the latter are:

- An unstable market where demand can fluctuate and become unpredictable (Jimo et al., 2019)
- Require customising components to serve specific needs (Klahn et al., 2014),
- Low volume or single components where short cycle time offer vast benefits (Tofail et al., 2018)
- A high degree of geometrical complexity (for example lattice, internal cooling channels) where conventional manufacturing methods are limited (Jimo et al., 2019)
- Short series production where it is not economically viable to use conventional manufacturing method (Jaster, 2019)
- Time constraints for example aerospace and medicine, where any delay in production can be catastrophic (Zadpoor & Malda, 2017)
- Consolidated design for multiple parts where structural integrity at joint may affect reliability and increase certification process (Klahn et al., 2014; Najmon et al., 2019; Puerto, 2015; SHINING 3D, 2020)
- Lightweights where the application requires lighter components for better functionality and cost-efficiency (Böckin & Tillman, 2019; Croft Additive

Manufacturing, 2020; Herzog et al., 2016; Liu & Shin, 2019; Najmon et al., 2019)

Industrial sectors where optimised designs, on-demand production and customisation are key to propel efficiencies are employing AM as a tool to enhance supply chain, production time, cost, material and energy efficiencies. Practical applications where companies have capitalised on the value added by metal AM (for example, L-PBF) are shown in Table 1.

Table 1: Comparison of derived benefits for components made by methods and L-PBF.

<table>
<tr><th>Combined derived benefits</th><th>CM methods</th><th>AM/L-PBF</th><th>References</th></tr>
<tr><td rowspan="5">• Integrated structure
• Bionic design
• Lightweight
• Reduced part counts
• Material efficiency
• Reduced waste
• Reduced manufacturing steps
• Reduced cycle time
• Better technical superiority
• Improved functionality
• Improved energy consumption
• Reduced life cycle cost</td><td>
</td><td>
</td><td>(Fitnik, 2020)</td></tr>
<tr><td>
</td><td>
</td><td>(GKN Sinter Metals Engineering GmbH, 2018)</td></tr>
<tr><td>
</td><td>
</td><td>(Aidro srl, 2020)</td></tr>
<tr><td></td><td></td><td>(Peng et al., 2020)</td></tr>
<tr><td></td><td></td><td>(Ren, 2019)</td></tr>
</table>

As can be seen from Table 1, metal L-PBF offers new ways to create an unprecedented revision of existing components by integrating internal flow channels, lattices and net-like structures to form optimised lightweight designs. Such designs often result in overall reduced manufacturing time, process steps, reduced inventory, quick change over, cost reductions and a simplified supply chain (Jimo et al., 2019; Plewa, 2019). Metal L-PBF potentially can rebuild or repair parts that may be out of supply or require too much time and conventional manufacturing via reverse engineering (Daraban et al., 2019). The outer geometries are collected via 3D scanning for reverse-engineered of the old component. Note that scanned data does not include any internal geometrical data. The collected cloud data points are converted to a CAD model where reconstruction and necessary adjustments are made (CRP TECHNOLOGY S.r.l., 2020; Plewa, 2019) followed by the sequential AM steps. The route to making part with reverse engineering always require pre-existing component. AM requires a synchronised approach to product design via the proper use of digital software. This is contrary to the conventional manufacturing methods that would firstly use a step-by-step approach to handle different aspects of product design before synchronising.

AM compared to conventional manufacturing methods continues to be an expensive option to manufacture components. Manufacturing companies have to consider the suitability of AM in making components that are possible with a conventional manufacturing method (Liu & Shin, 2019). For example, machining will an economical option to manufacture aluminium components if the component design complexity can easily be machined without difficulty. Aluminium also is an inexpensive metal (Herzog et al., 2016) that would be less expensive to process in the solid form than to produce the powder (feedstock) required for metal AM/L-PBF. Substituting machining with L-PBF for titanium components on the other hand might be easily decided due to the high buy-to-fly ratio, material cost and the difficulty to machine (Herzog et al., 2016).

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Appendix K: Examples of design optimisation

Appendix K1: Example cases of topology optimisation

The designing with no limits to creativity allows the creation of customisable, aesthetical and other design goals without adding to cost. 3D experience Catia, functional generative design software was used to create a 3D model and to optimise the design with FEA analysis. The performance of the bracket was simulated for the original design and the optimized design virtually. Digital simulations were performed to iterate design space to identify the optimal topology design. The goal of the design optimisation (see Figure 1) was to reduce mass (*m*) by 30% and to increase stiffness, (*k*). Stiffness describes the resistance a body exist against deflection or deformation to an applied force (Baumgart, 2000).

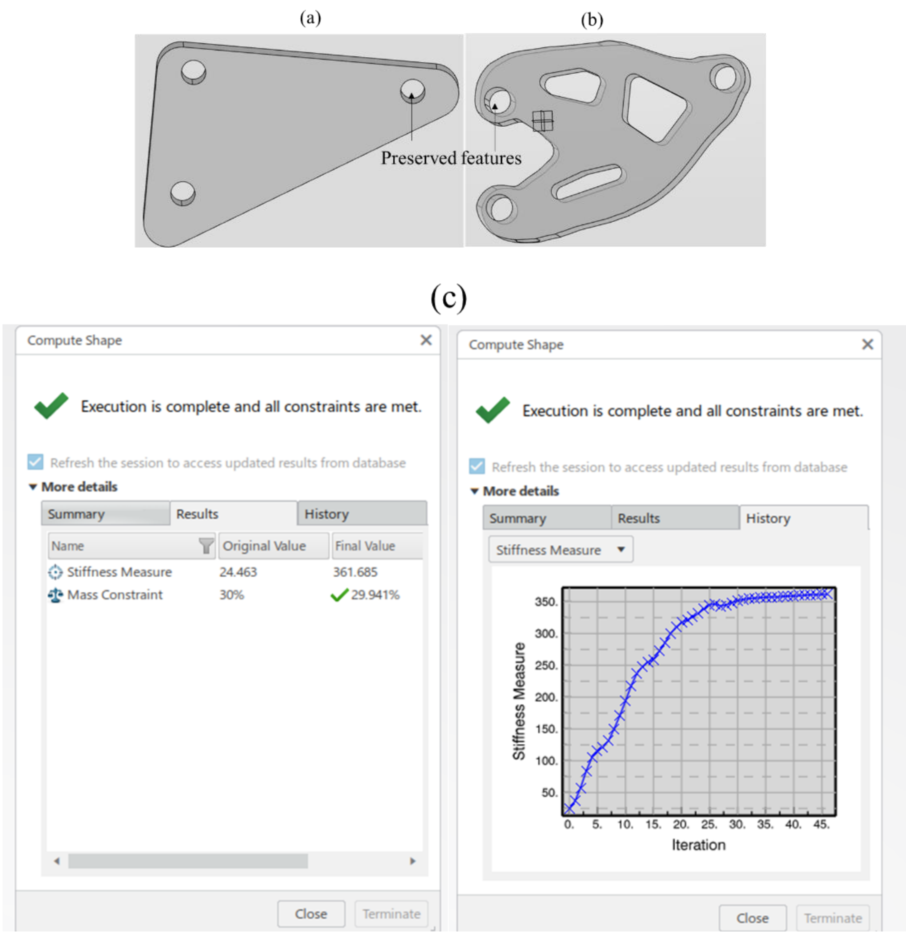

Figure 1: Illustration of (a) solid CAD model (b) simulation-driven optimised design and (c) design goals and several iterations by the author.

An illustration of design optimisation and simulated results to validate new designs are shown in Figure 2. The optimised bracket design inherently resulted in desirable weight reduction.

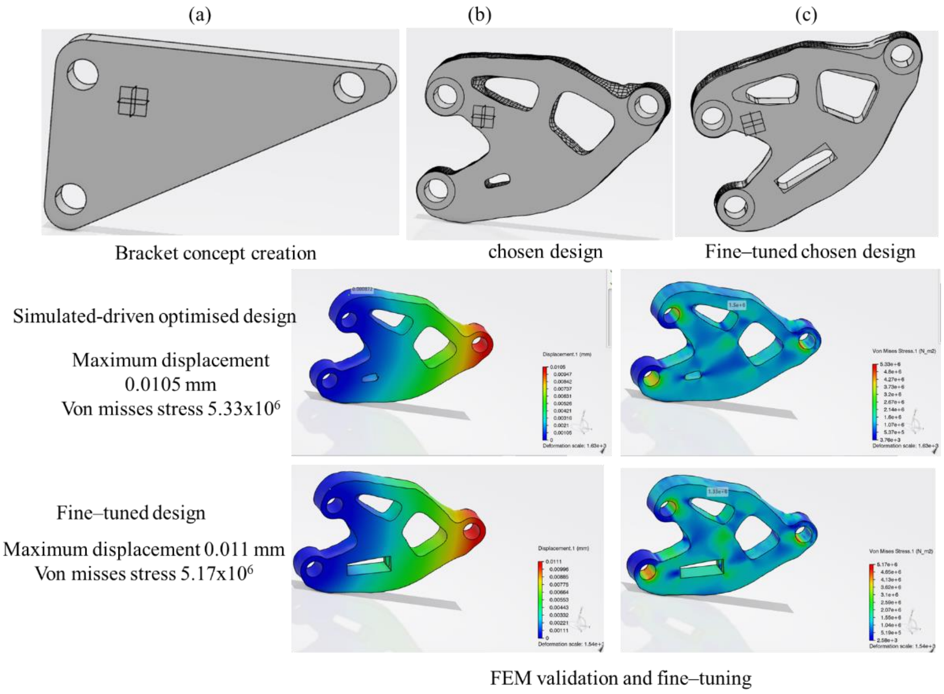

Figure 2: Illustration of topology optimisation (a) original design (b) automated optimised design (c) fine-tuned optimised design using 3DEXPERIENCE Functional Generative Design by the author.

The simulation of the performance of the new design shown in Figure 2b in comparison to solid bodies indicated improved functionality. Figure 2b, c effectively reduced the mass by 29.94% and the stiffness was increased from 24.46 to 361.6 N/m. The increased stiffness helped to withstand operational forces without deforming. This enhanced performance of the optimised bracket. Functional generative design software can create designs for both conventional and AM manufacturing methods.

Appendix K2: Example cases of lattice optimisation

Simulation allows for easy structure alteration within components to incorporate internal lattices. The nTopology software was used in lattice optimisation practice. Designing with no limits to creativity allows customisable designs to achieve aesthetical and better functional properties goals without adding to cost.

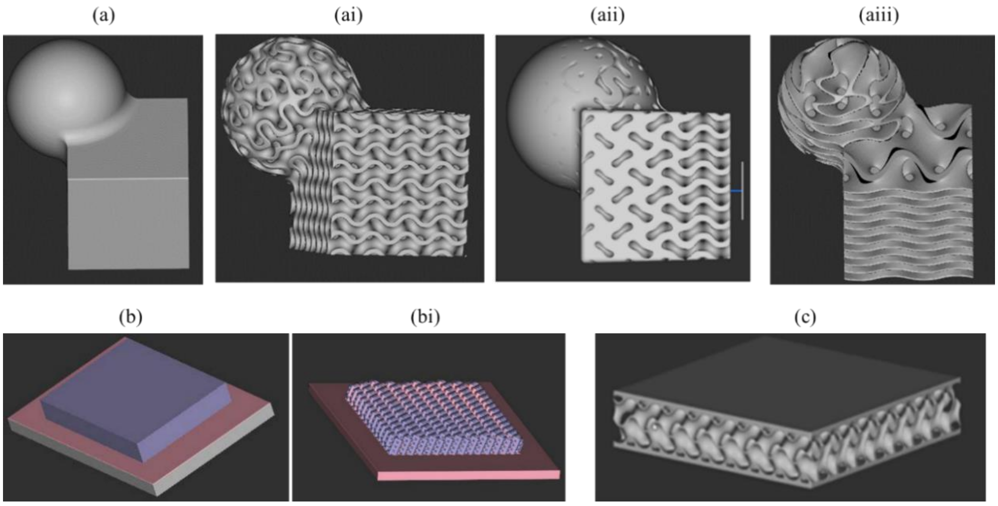

Figure 3: Automated lattice optimisation of (a) solid cube in (ai) (aii) and (aiii) and of integrated solid plates (b) in (bii) and (c) a sandwich plate designed with nTop software by the author.

The optimised structures shown in Figure 3 are almost impossible to manufacture with comparable CM methods. As can be seen from Figure 3a solid cube, Figure 3b integrated plates and Figure 3c sandwich plate solid regions of component designs are filled with lattices. Lattice optimisation can enhance both mechanical properties and the aesthetical appeal of components.

Appendix L: Examples of digital tools and workflow

Appendix L1: CAD modelling, simulation and virtual manufacturing software.

Examples of design, simulation software and the design goals that can be used in L-PBF to achieve specific benefits along a workflow are shown in Table 1.

Table 1: Examples of workflow and design simulation software in AM.

Process	Goal	Software/application	References
Design	• Define and prepare digital geometry	• Catia • SolidWorks • nTop • Inspire Print3D	(Altair, 2021; Dassault Systems, 2020; nTopology, 2021)
Simulation	• Predict performance of design according to design intent • Analyse design and process to optimise the design (topology, lattice optimization)	• Functional generative design. nTop • COMSOL Multiphysics • Ansys • Nefabb • 3DXpert • Inspire Print3D	(3D Engineer, 2020; Altair, 2021; ANSYS, 2017; Autodesk Inc., 2020; Campbell & Bourell, 2020; Chaplais, 2016; Corey, 2020; Dassault Systèmes, 2020b; Etteplan, 2020; Harris, 2019; nTopology, 2020)
Pre-processing	• Automate part positioning on the platform and allow interaction. • Automate relevant support structures. • Select process parameters like hatch distance and scan strategy	• VoxelDance • Powder bed Fabrication • Materialise Magics	(ANSYS, 2017; Campbell & Bourell, 2020; Voxeldance, 2020) (Campbell & Bourell, 2020; Doubrovski et al., 2015; Materialise, 2020; Praet, 2017)

(Continued overleaf)

Table 1 continued

Process	Goal	Software/application	References
Simulation manufacturing	• Plan part packing. Run virtual manufacturing to analyse stress and distortion	• Simulia Additive Manufacturing Scenario • Netfabb • 3DXpert	(3D Systems, 2020; ANSYS, 2017; Autodesk Inc., 2020; Chaplais, 2016; Dassault Systèmes, 2020a)
Monitoring and quality	• Perform online quality check of process • Evaluate consistent control of components	• Ansys. • EOSTATE ExposureOT • Sigma Lab's IPQA™	(ANSYS, 2017; EOS, 2020; Sigma Labs Inc., 2020)

Appendix L2: Example of reverse engineering workflow with simulation-driven workflow and AM

An example of the workflow for a hydraulic block design for a tractor engine using simulation-driven DfAM is illustrated in Figure 1.

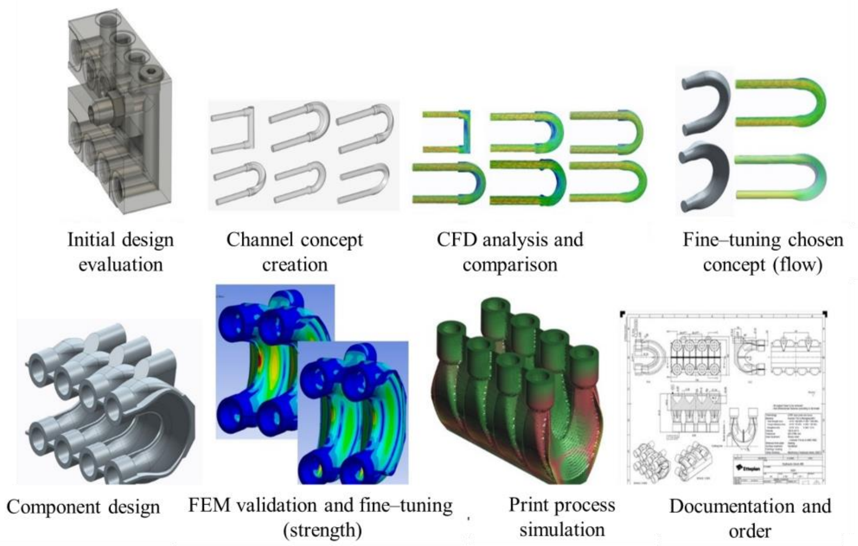

Figure 1: Example of workflow based on simulation-driven DfAM (Etteplan, 2020).

Figure 1 is an example of a workflow of component design and optimisation with simulation-driven DfAM.

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Appendix M: Supplementary data of P1 and P2

M1: Detailed design of the CAD models, manufactured components, manufacturing systems and machine levels.

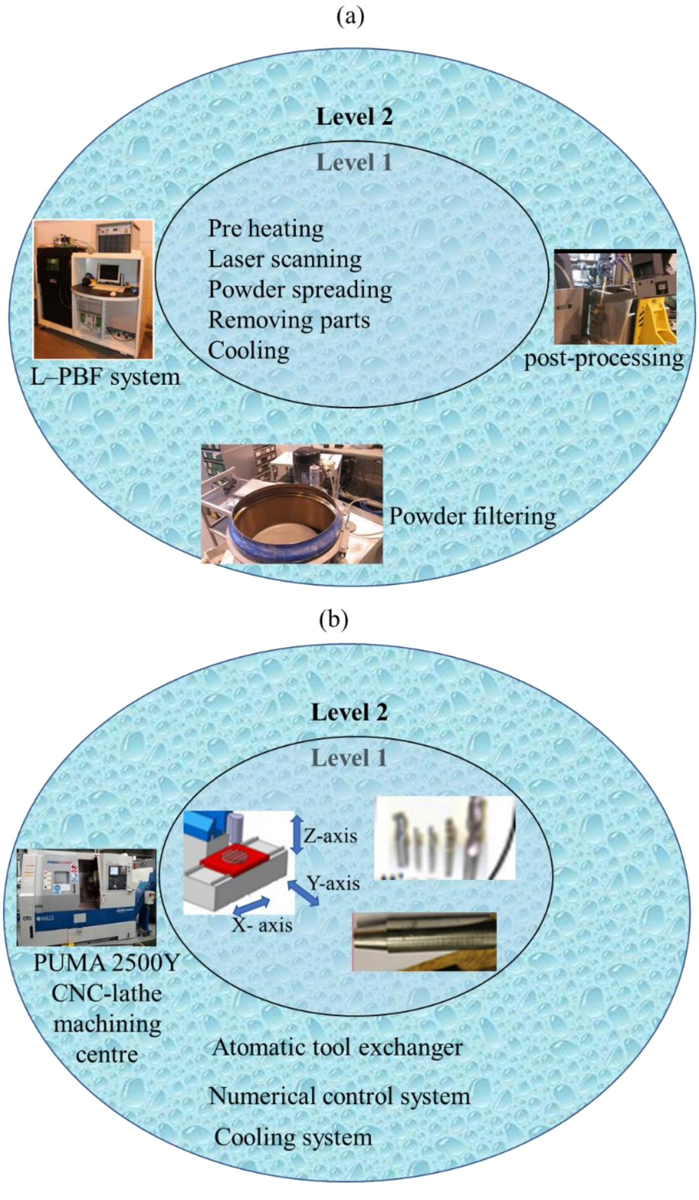

Figure 1: Representation of identified machine levels of (a) L-PBF (b) CNC machining in **P1**.

Appendix M2: Manufacturing machines

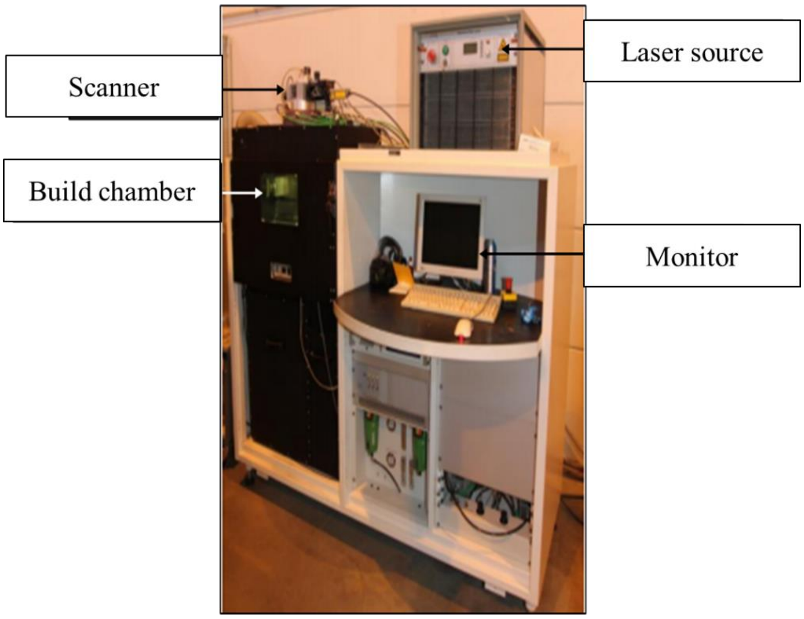

Figure 2: Representation of the modified L-PBF system and set up.

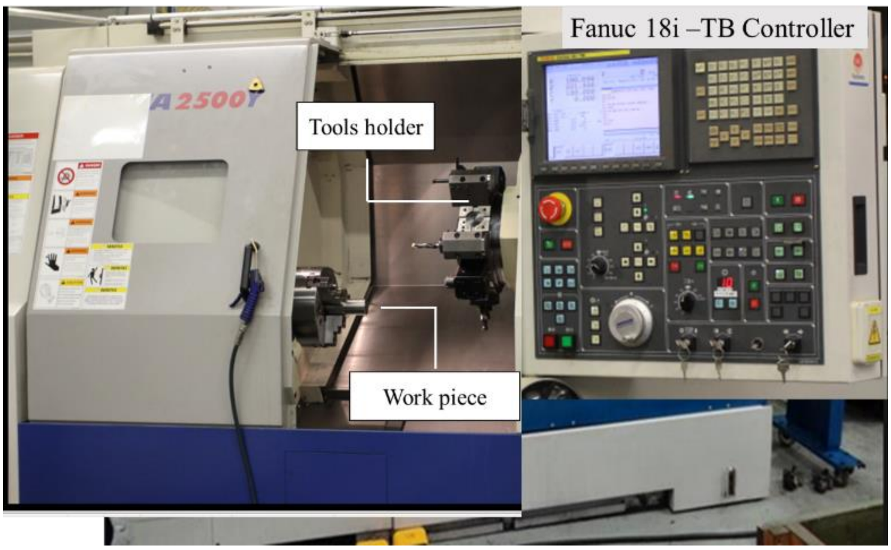

Figure 3: Representation of the PUMA 2500Y CNC-lathe machining centre and machining set up.

Appendix M3: Detailed CAD models

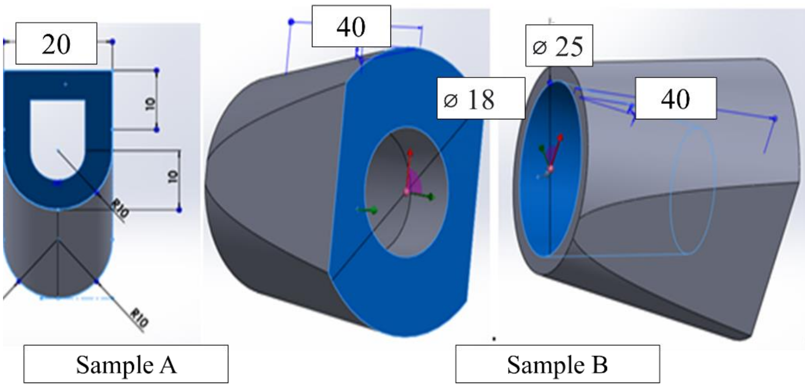

Figure 4: Representation of CAD models with dimensions of samples A and B.

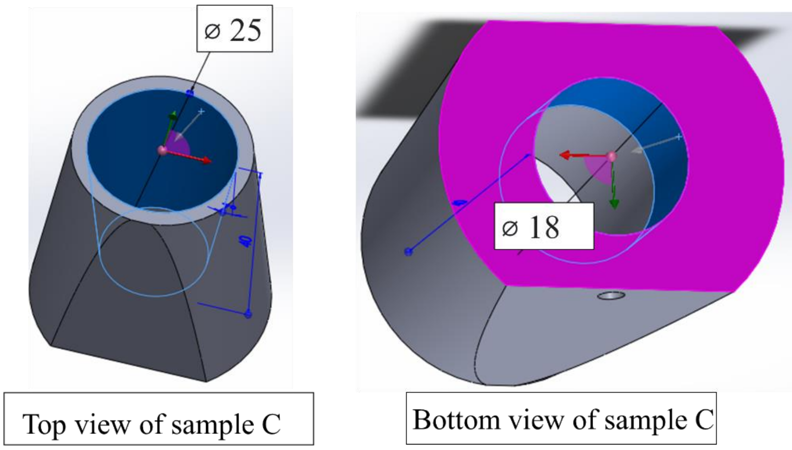

Figure 5: Representation of CAD model of sample C and unfused powder escape gates (2 mm).

Appendix M4: Manufacturing procedure and ready samples.

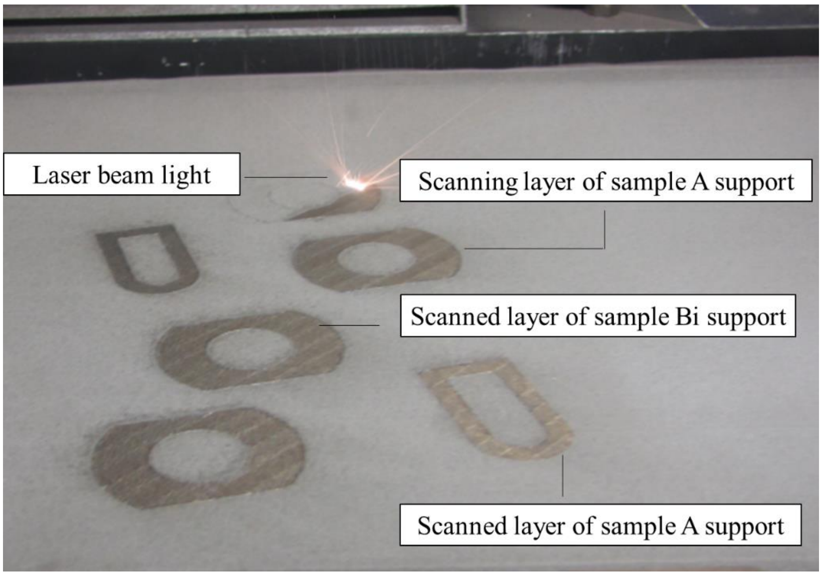

Figure 6: Representation of scanning of a layer of samples on laser powder bed fusion chamber.

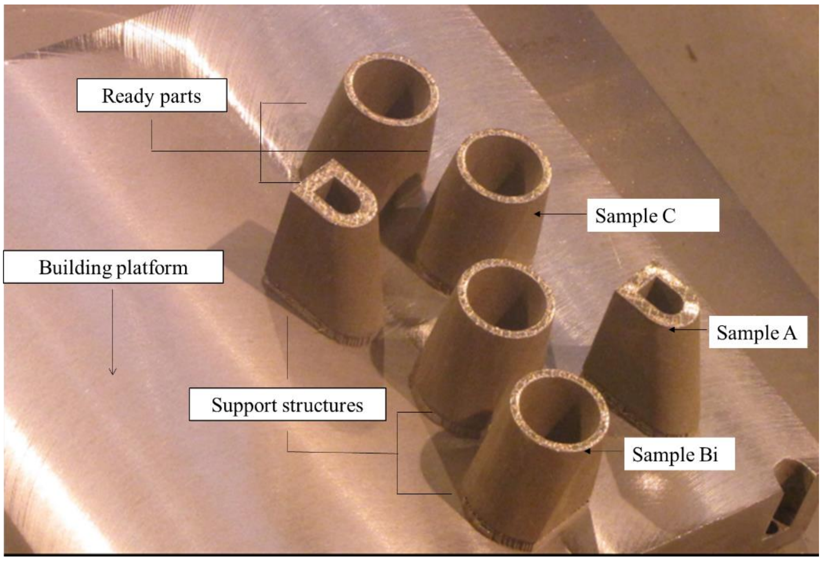

Figure 7: Representation of as-built parts of samples A and Bi attached to build platform.

The result of the preliminary LCI study in this thesis showed that the environmental impacts of AM can be evaluated throughout the service life of products. The benefits of reduced environmental impacts are shown with the reduced material and process fluids consumption reduced waste and reusability of raw material. The ability to make lightweight components for dynamic applications enhances fuel efficiency during the use phase and reduces the quantity of emissions. The nature of metal L-PBF nevertheless inherently limits the scope and data availability as certain aspects of information are kept secure within respective companies. For instance, contributions of powder production in ongoing LCA studies are often based solely on existing theoretical values of energy and material consumption indicators. Empirical based LCA assessment to include powder production will enhance aspects of L-PBF to sustainability.

CNC machining of sample Bii

There were five different machining processes performed per each of the sample Bii as one process could not produce the desired shape. Each phase of machining was performed machining centre, sequentially on the PUMA 2500Y CNC-lathe machining centre.

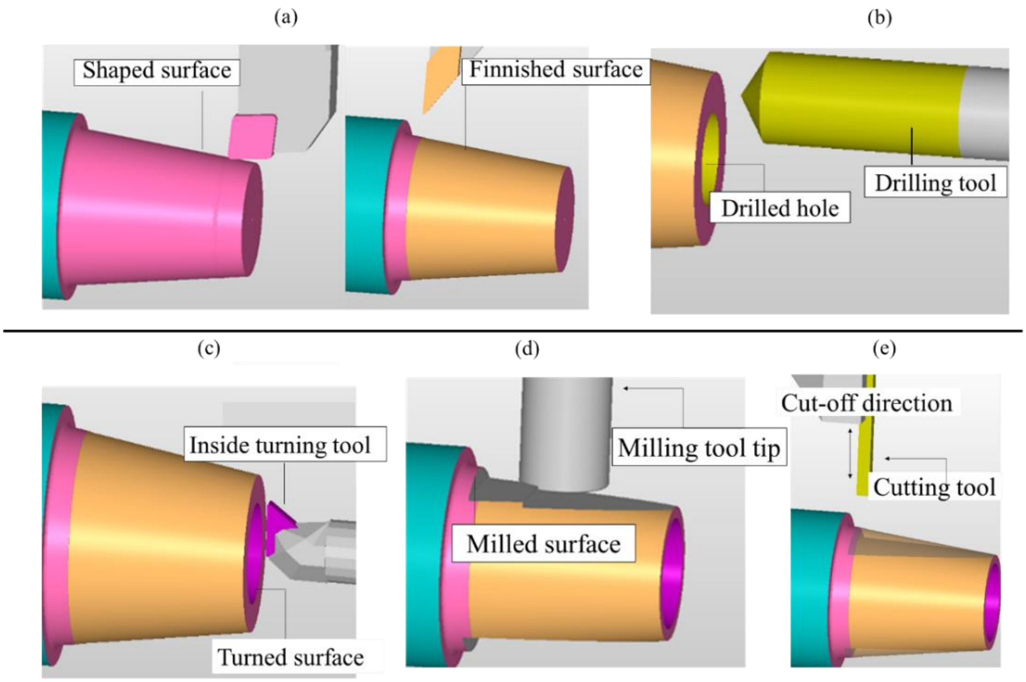

Figure 8: Representation of turning, drilling, milling and cut-off operations used to manufacture sample Bii.

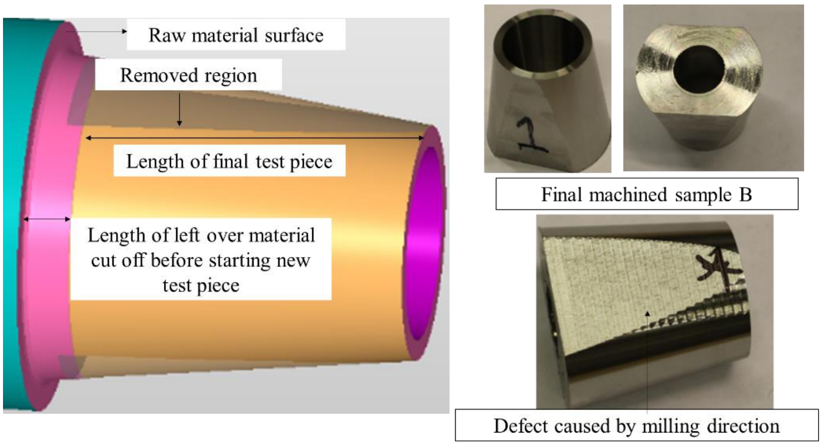

Figure 9: Illustration of the raw material, final parts and effect of possible machining defects.

Appendix N: Supplementary material for P3 and P4

Appendix N1: Experimental set-up, process parameters, samples and comparison of the result.

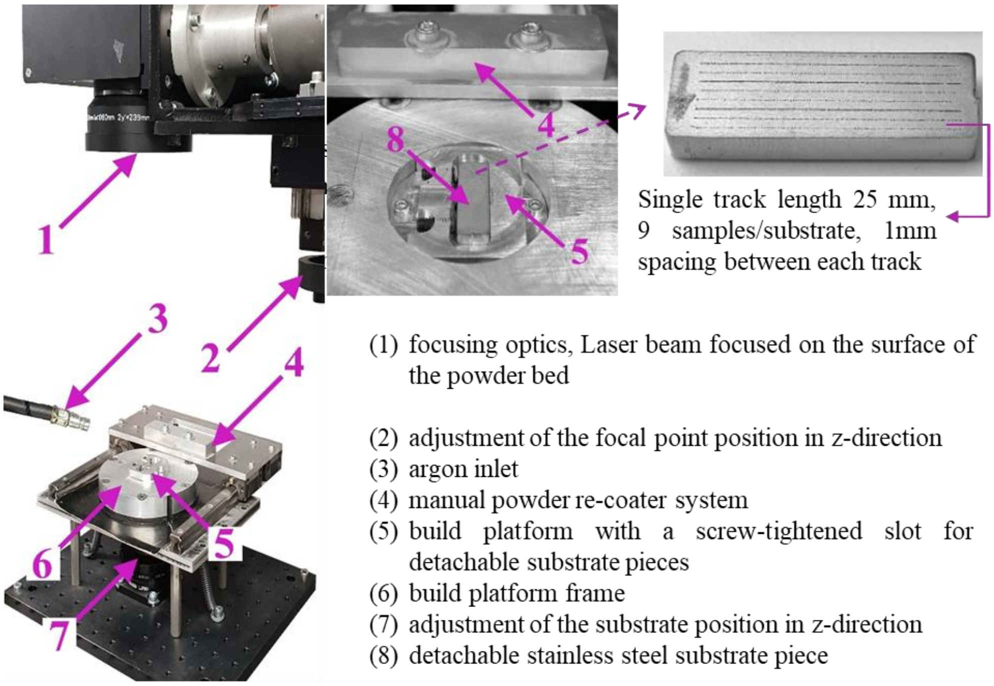

Figure 1: Illustration of in-house developed system and experimental setup L-PBF system, (image copyright Laitinen, V.).

There was a total of 162 single tracks with L-PBF(P) in 18 patches with 9 tracks per each. There were 36 tracks with L-PBF(CW) in 4 patches with 9 tracks per test substrate. Six constant values of *VED* (between 36 and 120 J/mm^3) were used by adjusting the scanning speed (9–489 mm/s) using equation 1 were used for L-PBF(P).

$$VED = \frac{Pavg}{d.v.t} \qquad (1)$$

Table 1: Process parameters used for L-PBF(P) and L-PBF(CW).

Parameter	L-PBF(P)	L-PBF(CW)
• Pulse length (µs)	• 50,100,200	• -
• Volume energy density	• 36–120	• 36–120
• Peak laser power (W)	• 80, 135, 190	• 30–190 (20) Average=peak
• Pulse repetition (Hz)	• 1100, 1500, 1900	• -
• Powder layer thickness (µm)	• 50	• 50
• Scanning speed	• 9–489	• 49–1030

Appendix N2: Overall life cycle model with and the major cost driver in metal L-PBF.

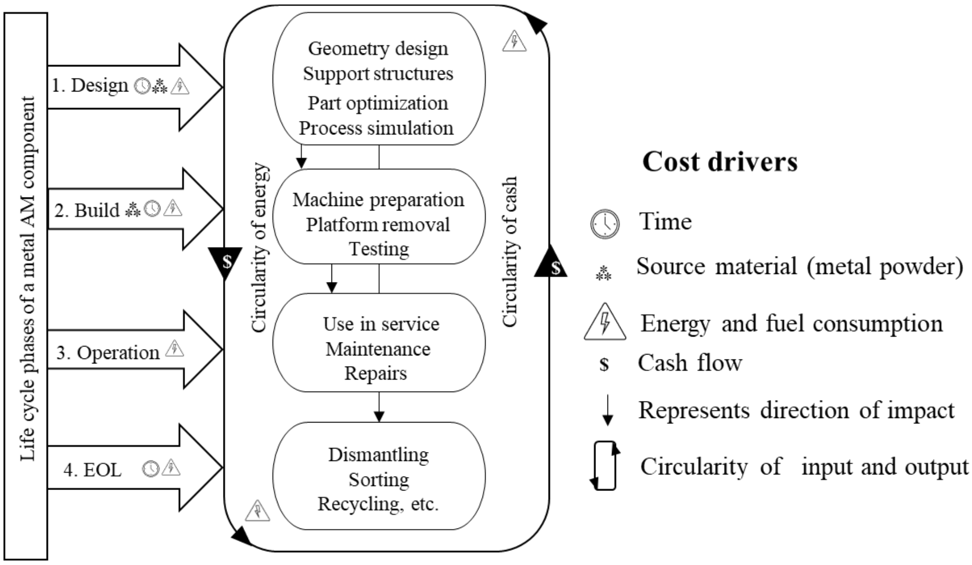

Figure 3: Representation of initial created LCC model for metal L-PBF with main cost drivers.

Appendix O: Summary of industrial discussion

Engineering dimensions of manufacturing chains use an incredible amount of effort to rationalise known and unknown claims which often contain levels of details. These claims are often only comprehended and appreciated by other engineers and often are farfetched for the perspective users to articulate benefit. Industries integrate capabilities and creativities of marketing and sales of the business to make simplified and meaningful pitches of core products designed by engineering. Industrial companies often deal with customers who seek swift answers and advice to the financial benefits offered by L-PBF. The benefits of metal AM/L-PBF are often evaluated based on component alone and this may not effectively communicate to potential users. Practically showing for example 30% weight or cost reduction benefit may not be enough reason to redesign without a comprehensive assessment of function to other components. Companies may be reluctant to change to metal AM but showing the overall life cycle benefit is a good direction of approach. Having a model that can show the wholeness of the added value of metal L-PBF component in relation to other components is important. Such models will inform the total advantages in relation to the overall value chain throughout the service life of components. A feasibility study at the early stage can for instance consider the benefit of Metal AM/L-PBF components to a whole machine assemble. Questions, for example, using metal AM/L-PBF for gear drive unit can be:

- Will using a metal L-PBF manufactured gear drive unit with a 30% reduction in original weight affect the overall weight of the machine assembled?
- Will the replacement of a lighter gear drive unit improve performances by reduced weight and motors size (for example, replace big with small)? and
- Will intricate and lightweight components also contribute to reducing materials usage, energy consumption, the function of machine assembles and operational cost?

Metal L-PBF could potentially save raw material, fuel consumption, lead time and cost throughout the life cycle of components. The costs and time saving offered by metal L-PBF may be visible. A school of thought might argue that the process is slow and thus increases manufacturing time and cost. Others may also argue that the benefit of making lightweight components exceeds the long build time and energy consumption during the manufacturing phase. The justification of the importance must consider the overall lifetime savings of material consumption, energy consumption, time and cost reduction. Adoption to metal AM/L-PBF must be planned to produce high-value and reliable functional components where CM methods are technically, economically and sustainably not feasible. The contributions to sustainable manufacturing in respect to resource efficiency and profit gains must be shown from design, manufacture, use and EOL phases to aid acceptance. Decision-making will require fulfilling the needs of customers to keep a competitive edge. The demands of customers can be multi-goal orientated, for example, a customer may ask for a cost reduction, improved functionality, aesthetics and with a tight schedule and cost. This means that innovating one concept at a time is no longer an effective sustainable approach.

The first revision of the developed LCC-driven DfAM model in Publication 4 (see Figure 4.8) highlighted the possibility of an added value of replacing metal AM/L-PBF components of a machine assembly. The replacement of replacing optimised metal L-PBF manufactured components can also result in the downsizing of other components in a machine assembly. This added value was only realised during the discussion with the industrial representatives.

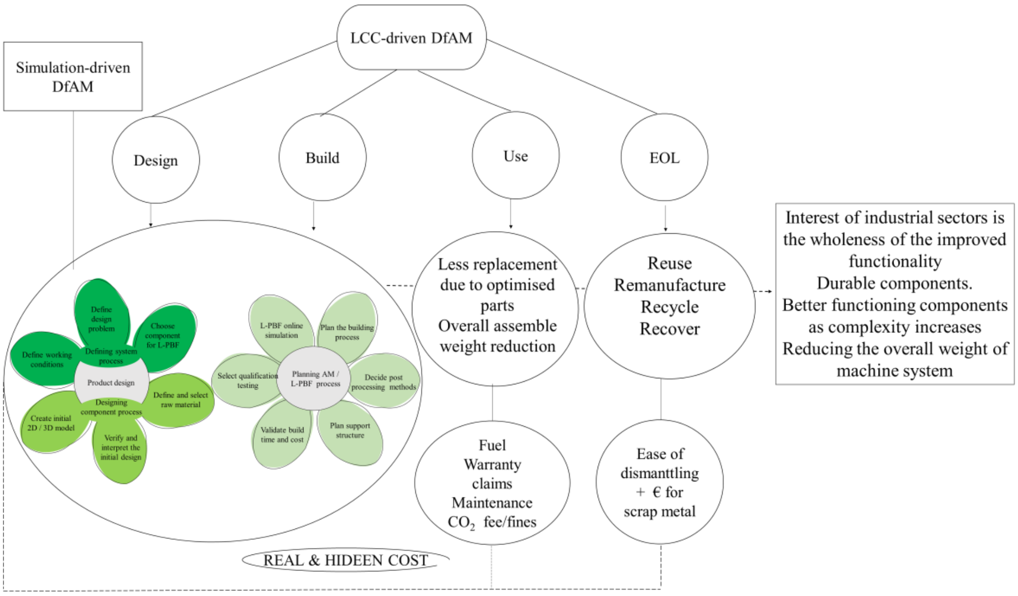

Figure 1: Illustration of the first review of the DfAM model from an industrial perspective.

Identifying the additional positive outcomes of increased functionality and saving in other components highlights the importance of AM/L-PBF. These can show how replacing an existing design with optimised metal AM/L-PBF component improves the functionality of other components.

Appendix P: VCA scenarios of metal L-PBF

The two propositions of VCA offers companies the means to identify activities that add value to their core product and to analyse the activities to either reduce costs or increase differentiation. Manufacturing companies need to consider the overall benefit of an assembly along the value chain whether an intended component is suitable for metal L-PBF. Consider the part design, whether using L-PBF will increase functionality, cost, efficiency, aesthetic, customisation and complexity, depending on the use case. This will help in deciding as to whether using metal L-PBF will be beneficial and to identify the best entering position along the value chain.

Case 1: Example case is original equipment manufacturer (OEM) that invests in the L-PBF machine/s for mass customisation or serial production for gear drive component. Performs system design, geometry design, the building of components, post-processing and assembling of the component as illustrated in. Figure 1.

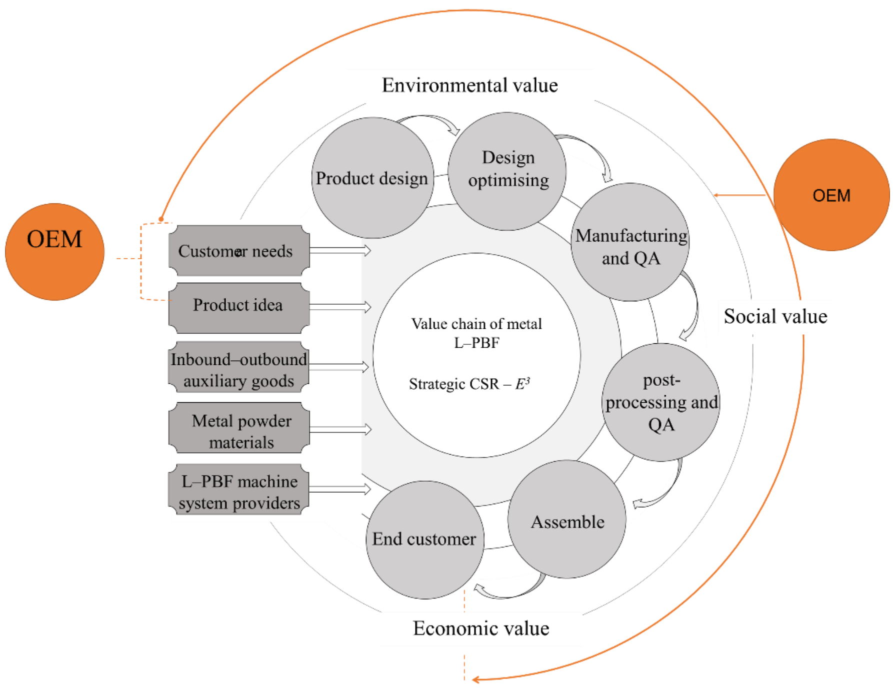

Figure 1: Applicability of VCA for OEM machine builder that invests in the L-PBF machine/s.

As can be seen from Figure 1, OEM using L-PBF can adopt the process to create common values that will satisfy both cooperative and sustainability goals along the value chain. The areas marked in orange colour indicates the value chain belonging to the manufacturing chain. The activities carried out within companies must be done in consideration of creating environmental, social and economic values. Adding value to an

L-PBF component incur no adding extra cost. This benefit must be effectively communicated to new customers who may be more accustomed to high value-high costs in conventional manufacturing systems.

Case 2: Example case is an OEM company that use service providers to design and manufacture gear drive unit of machine assembly. The end customer defines the intended functionality and working conditions. OEM, in turn, communicates these functional requirements to a third-party company (sub-contractor) to outsource the designing, manufacturing and post-processing of components as Figure 2 shows. The OEM may perform system design and geometry design in collaboration with service providers.

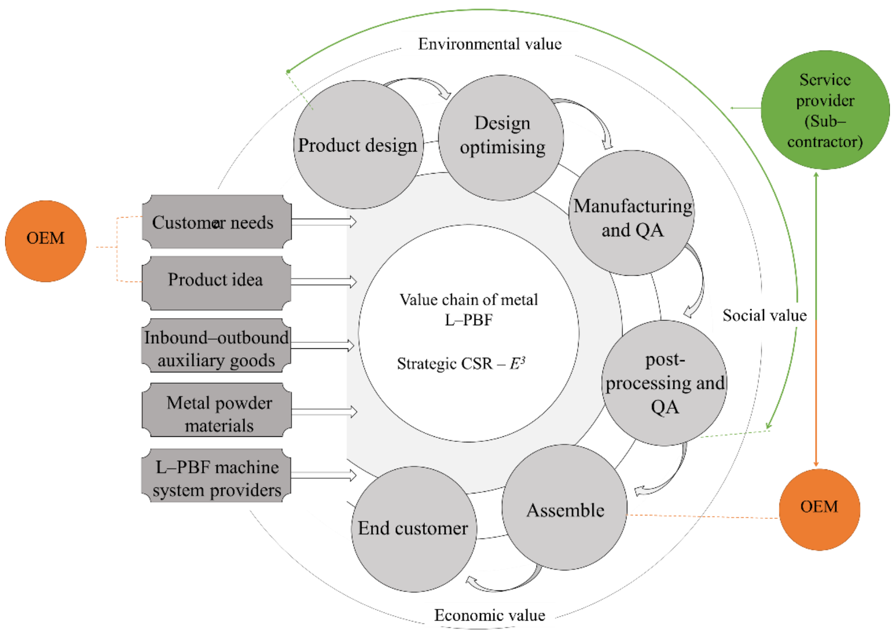

Figure 2: Applicability of VCA for OEM machine builder that outsources L-PBF components.

As it can be seen from Figure 2 OEMs may engage the services of service providers along the value chain for metal L-PBF components without having to invest in the machines. The area shown in green colour corresponds to activities that may be outsourced in this case. Service providers and subcontractors who consider LCC saving during the design of components will attract more benefits for OEMs and improve attractiveness on the market than competitors who do not consider such lifelong benefits.

Appendix Q: SWOT scenarios of metal L-PBF

The usefulness of SWOT in adoption to metal L-PBF can be defined based on the use case (Figure 1 and Figure 2) within manufacturing industries. A company that only outsources a design to a service provider will not see the strength and threat of having DfAM simulation software whereas the service provider will consider the impacts of DfAM guidelines. Making such distinction clarifies the benefits such models can offer for different users along the value chain. The costs of design, engineering, hardware and software may be considered a threat depending on the position of the user. Service providers who make serial production for multiple customers may view investing in metal L-PBF machines as an opportunity to compete and in fact as an asset whereas a company that acquires the machine for in house production might consider the initial investment a limitation.

Case 1: OEM machine builder that invests in the metal L-PBF machine/s for the gear drive unit.

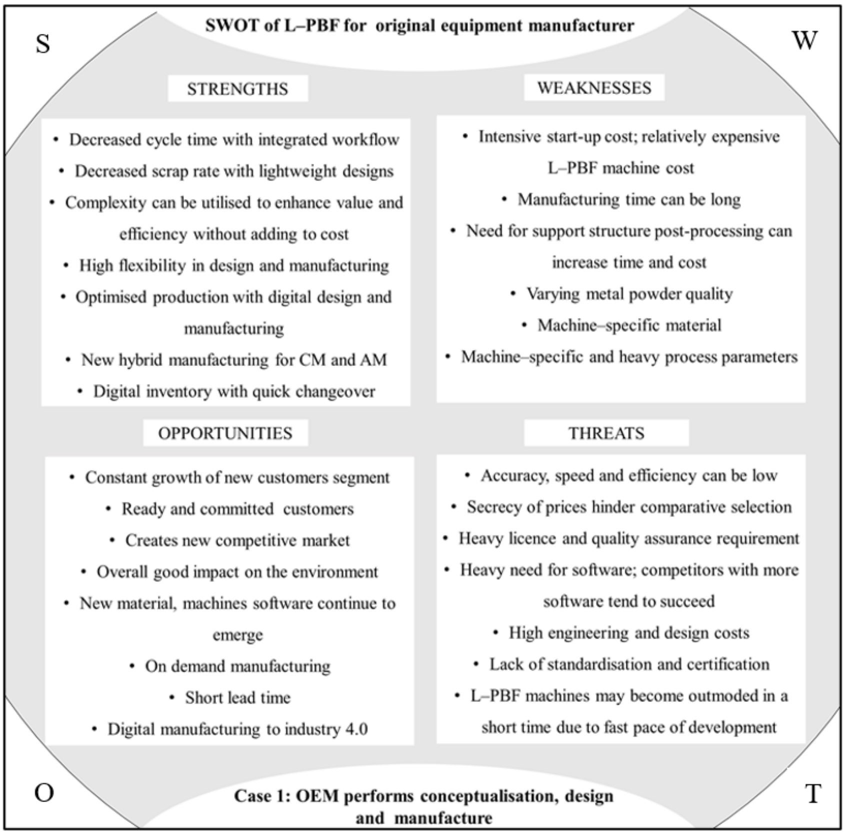

Figure 1: SWOT analysis of L-PBF based on OEM that designs and manufacture components internally.

Case 2: OEM that outsources design and manufacturing of gear drive unit to a service provider.

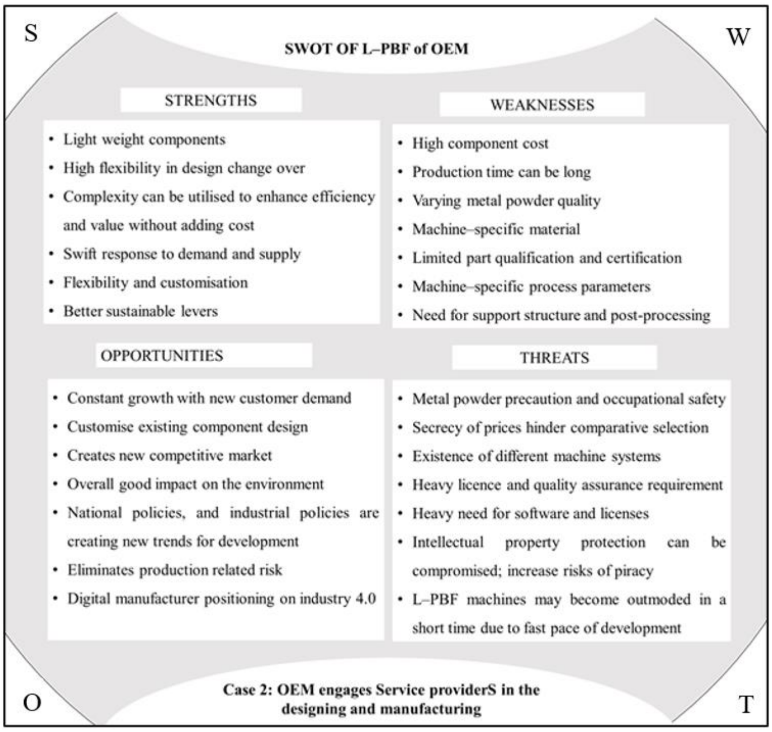

Figure 2: SWOT analysis of L-PBF based on OEM that outsources design and manufacturing of L-PBF components.

Performing SWOT analysis of metal L-PBF as Figure 1 and Figure 2 show can help gain an understanding of how the method may be used to generate maximum benefits and reduce negative environmental and economic impacts. This can enhance the competitive edge for companies who adopt metal AM/L-PBF in either internal/external or existing/new markets. As can be seen from Figures 1 and 2 the use of SWOT analysis can help identify weaknesses and threats that can be used to guide the decisions making to be able to control environmental and economic performance. The given points are the only example of how a company may analyse their internal strengths, weakness and external opportunities and threats. Manufacturing companies who consider entering metal L-PBF and find SWOT analysis prudent must do so with the aim to:

- Strengthen advantages and take measures to reduce weaknesses
- Identify the opportunities and take measures to reduce threats

Appendix R: Strategic approach to enhance efficiency in L-PBF

The acquisition of simulation-driven DfAM software or L-PBF machines do not necessarily translate to increased efficiency. There is a need for management to monitor process effectiveness (the right way) and efficiency (right things). Effectiveness at the managerial level is to do the correct things and demonstrates how well a procedure satisfies a request. Basically, managers in manufacturing industries must ensure that the skills of personnel, tangible and intangible resources are appropriately used to satisfy the objectives of the company and the desires of customers. Efficiency is the right use of the right things, for example, the right usage of the available resource (machines, equipment, materials, software, workforce, time and so on). Efficiency involves resource consumption improvement alongside a decrease in waste. Improvement of the cooperation between managers and value changers within metal L-PBF can guarantee effective and efficient working for benchmarking the process and cost models. An effective procedure to do the right things integrated with efficient use of material, software and equipment must be maintained to ensure the effectiveness of components to overcome potential shortfalls and give the needed value for companies. Several different strategies such as communication, research support, training to increase skills in the workforce and provision of adequate digital software are needed to control resource efficiency, cost-efficacy and promote wellbeing and inclusiveness of all personnel. Figure 1 is a schematic of required efforts that potential and existing L-PBF companies could adopt to overcome shortfalls that may hinder the realisation of the benefits of metal AM/L-PBF.

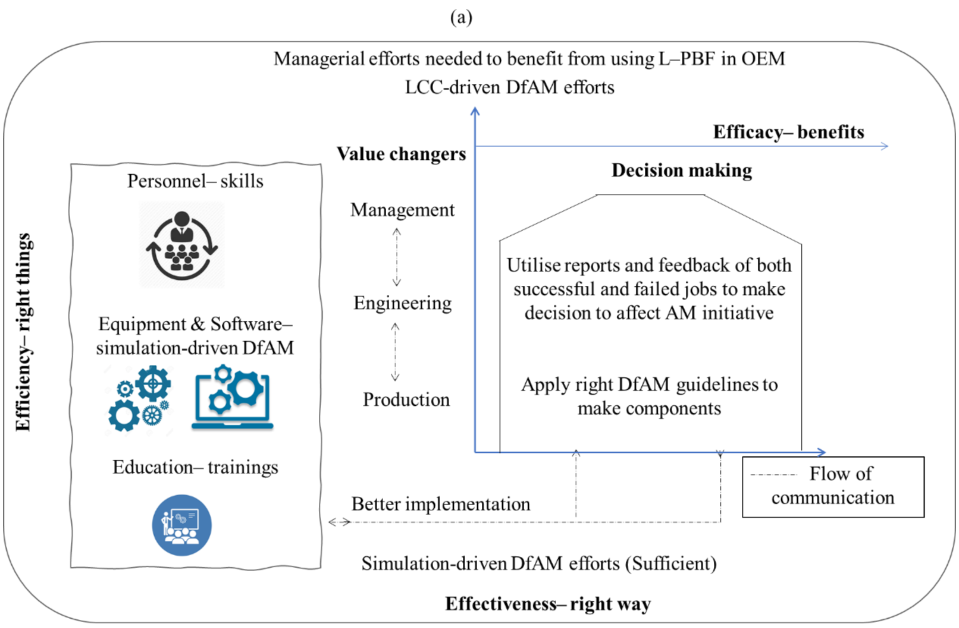

Figure 1: Representation of strategic planning to the adoption of metal L-PBF in OEM.

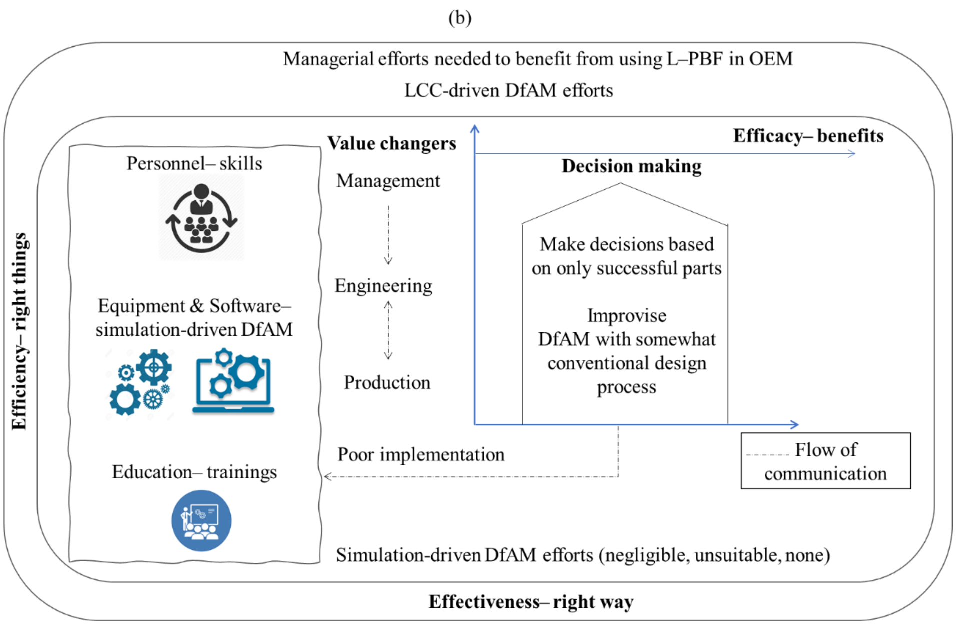

Figure 2: Representation of strategic planning to the adoption of metal L-PBF in OEM.

The model in Figure 1 is an example of an adoption plan for OEMs that consider investing in the metal L-PBF. This model depicts how OEMs can use the flow of information to improve cost and productivity within the levels of management and value changes. The adoption plan in Figure 2 shows a reciprocal or interactive scenario of communication between the different operational levels. This strategy requires all levels of personnel to understand specific L-PBF design rules and make decisions considering both successful and failed components. Decision-makers can leverage efficient and effective integrated digital value chain and added value time to attain improved productivity from respective value changers and value time. This is because metal AM will increase material efficiency and create components of a higher value that can offset the high energy consumption when the right things and right ways are used. The adoptive plan in Figure 2 shows a one-way flow of communication. This strategy may improvise DfAM guidelines with traditional design for manufacturing and assembly (DFMA) rules or at best apply generalised DfAM rules for metal L-PBF without considering the process-specific features. Top management does not understand the need for simulation-driven DfAM. Decisions made in such instances are bound to be based on successful or failed components without considering the root causes.

Publication I

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Overview of sustainability studies of CNC machining and LAM of stainless steel

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Overview of sustainability studies of CNC machining and LAM of stainless steel

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Abstract

Laser additive manufacturing (LAM), known also as 3D printing, is a powder bed fusion (PBF) type of additive manufacturing (AM) technology used to fabricate metal parts out of metal powder. The development of the technology from building prototype parts to functional parts has increased remarkably in 2000s. LAM of metals is promising technology that offers new opportunities to manufacturing and to resource efficiency. However, there is only few published articles about its sustainability.

Aim in this study was to create supply chain model of LAM and CNC machining and create a methodology to carry out a life cycle inventory (LCI) data collection for these techniques. The methodology of the study was literature review and scenario modeling. The acquisition of raw material, production phase and transportations were used as basis of comparison. The modelled scenarios were fictitious and created for industries, like aviation and healthcare that often require swift delivery as well as customized parts.

The results of this study showed that the use of LAM offers a possibility to reduce downtime in supply chains of spare parts and reduce part inventory more effectively than CNC machining. Also the gap between customers and business is possible to be shortened with LAM thus offering a possibility to reduce emissions due to less transportation. The results also indicated weight reduction possibility with LAM due to optimized part geometry which allow lesser amount of metallic powder to be used in making parts.

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Keywords: Additive manufacturing; stainless steel; conventional manufacturing; supply chain; sustainability

1. Introduction

The increase of added value to products as a result of improved productivity and efficiency due to existing and emerging manufacturing methods cannot be overemphasized (Manyika et al., 2012). These methods potentially offer benefits for both high quality products and process efficiencies. Laser additive manufacturing (LAM) is one of the methods, which has been identified to offer such benefits (Yoon et al., 2014).

LAM is able to make parts using the exact amount of powder needed for final part and almost all surplus powder may be reusable. This method is able to produce parts closer to end users as well as eliminate any additional transportation of preformed as raw material to manufacturing centers as starting material for conventional processes. CNC machining for instance may require voluminous metal bars or plates as startup from which only small amounts remain as final part. The acquisition of right size of initial material in conventional processes may often result in delays in operations. Manufacturing companies may not have needed startup material in their stock-keeping-unit as using over dimensioned stock often increases production cost and even result in material wastage. This is because starting production as close as possible of the exact stock is preferred as both price and material efficiency can be achieved. The possibility to build parts with negligible amount of waste and with a better supply chain flow are core to application of LAM.

Life cycle thinking can be seen as a concept to attain the objective of sustainability. Life cycle thinking means widening the traditional view from manufacturing processes to include various aspects related to the product over its entire life cycle. Life cycle management (LCM) is a voluntary framework to implement life cycle thinking and the objective of sustainability into the industry. To have sufficient effect LCM needs to be involved in all the levels of the organization such as management, distribution, sales and marketing, production, procurement, and product development. (Remmen et al. 2007). This paper discusses the possible sustainability benefits of LAM in the procurement, production and distribution.

Nomenclature

AM	Additive manufacturing
PBF	Powder bed fusion
CNC	Computer numeric control
CO2PE!	Cooperative effort on process emissions in manufacturing
DED	Direct energy deposition
EOS	Electrical optical systems
ECUs	Energy consuming units
JIT	Just in time
LAM	Laser additive manufacturing
LCI	Life cycle inventory
LCM	Life cycle management
SEC	Specific energy consumption
UPLCI	Unit process life cycle inventory

Huang et al. (2012) have shown in their study that additive manufacturing can be promising in three main areas of operations. The study indicated as possible improvements achievable with AM (Huang et al., 2012).

1. the ability to create individualized parts that can function effectively for better healthcare and quality of life,

2. the capability to reduce environmental impacts of manufacturing, and the potential to simplify supply chain that may offer maximal efficiency and
3. alertness in responding to demand with satisfaction.

Sreenivasan et al. (2010) points out in more detail that the specific points of product life cycle where environmental benefits, such as greenhouse gas emission reduction, might occur are the reduced need to mine and process raw material ores due to increased material efficiency, ability to design more energy efficient products via enchanted cooling methods, the decreased fuel-consumption due to lighter vehicles in transport-related products.

World Economic Forum (2013) and European Commission (2013) have estimated that the supply chains with LAM might shorten as parts are possible to be built closer to customers with improved intermediate connections. The studies indicate that instead of the traditional supply models that often required several stock-keeping units, modern model of doing business such as just-in-time (JIT) are feasible with LAM. This is thought of as possible as the gap between customers and manufacturer get shortened with decentralization and as well as reduced led time. World Economic Forum (2013) claims that the use of LAM might improve sustainable gains in terms of material efficiency and might also result in better transportation systems as improved packaging are used during shipment. LAM is believed to reduce costs as well as fuel consumptions in airlines that use new engines parts made with this technique as a results of the lightweight of components made possible either as hollow or net shaped structure (World Economic Forum, 2013; EC, 2013).

The use of life cycle assessment oriented methods may highlight the potential and accuracy to measure product and process efficiencies in discrete manufacturing like LAM. A method that exist as a guide for systematic life cycle inventorying analysis for discrete manufacturing is CO2PE! UPLCI Initiative. This method has been previously been applied for LAM by Kellens et al. (2012) and is explained in more detail in part 3 of this paper. Duflou et al. (2012) identified in their study that there are large discrepancies on the energy demand of discrete part manufacturing processes obtained by different assessment methods. This paper gives an example on how to conduct an “In-Depth approach” to metal LAM process to facilitate the acquisition of process specific data.

1.1. Supply chain in LAM

Perumal (2006) have shown in their study that the main characteristics of an excellent supply chain are a delivery of high quality products to customer responses, efficient converting of inputs into outputs and improvement of asset utilization e.g. leveraging inventory and working capital (Perumal, 2006). These elements can affect the merit of spare parts supply chains managing as the focus must also be on the reduction of operating cost without altering wishes of customer. There may be challenges that might oppose the achievement of such objective like unavailability of parts or delay of production. One challenge that has remain persistent over time is the unpredictability of demand, especially for new product launches for which the data on parts failure rates may be unreachable which may lead to delays in production. A high inventory is usually the only option for companies to overcome this challenge. A lot of additional burden may be imposed on companies as unused parts may have to be substituted, recycled or even landfilled as a result of wrong specifications. Another problem could be the need to support both old customers and new customers. This responsibility can in large extent require management to keep large unit stocking in order to meet the pre-and after sale request or changes. Thus greater workforce, larger amount of parts and tools may be needed to be managed simultaneously which foretell increased responsibility of management.

A solution to these and other similar problems are not far-fetched. As having an all-inclusive system that can work properly to eliminate or reduce these shortfalls in operations of firms is a sure yardstick to reduce some of the inefficiencies in companies. AM might be one solutions to overcome such problems in manufacturing companies. Some professionals believe also that AM will totally transform manufacturing supply chains.

The analyses of sustainable developments are tied to manufacturing and transportation operation (Nyman and Sarlin, 2013). However, the value chain in manufacturing companies in recent times are becoming increasingly long and complicated making it more vulnerable than ever before. As a result its supply chain have changed to occur over long and broadened scope with an increasingly complex relations (Mentzer et al., 2001).

1.2. Sustainability in LAM

Gunasekaran and Spalanzani (2012) have shown that sustainability benefits of LAM can be seen from the possibility to improve swiftness in operation and raw material efficiency. Sustainability and customized products are increasingly becoming fundamental basis for competition in engineering industries. The reduction of many of the ancillary process aid and the numerous preparation steps often needed in comparable conventional processes in fabricating products are the benefits of LAM. LAM can also improve material efficiency considerably. Conventional manufacturing often requires specific form of startup material from which parts are removed as waste in order to get final parts. The amount of stock needed and also need for transportation might be reduced when using LAM. (Nyamekye, 2014).

A collaborated study between EOS, Filton branch England and Airbus Group innovations compared the lifecycle of two critical technologies rapid investment casting and LAM of stainless steel bracket for Airbus A380 (EOS, 2014). The goal of their study was to evaluate rapid investment casting and PBF for a standard Airbus structural part, including detailed aspects of the overall lifecycle. The study which was adapted from streamlined lifecycle assessment of Airbus and ISO 14040 series requirements data aimed to serve as basis for further preliminary closed loop analysis into other aerospace parts, processes, and end-of-life strategies. Figure 1 shows the two designs of brackets used for the study.

Fig. 1. Prototype of an optimized Airbus A380 bracket manufactured with AM (front) and investment casting (back) (EOS, 2014).

As it can be seen from the Figure 1, considerable amount of material could be assumed to be saved as a result of the net-like design of the AM part. The study also propose that designing complex geometry, as shown in the front model for dynamic applications, might reduce emissions as weight of parts are reduced. A further potential of increasing functionality of components whiles decreasing cost of operation in aviation industry were also highlighted.

Yoon et al. (2014) have similarly compared in their study polymeric additive manufacturing (AM) methods, and traditional processes like injection molding and machining (e.g. milling and drilling). Their study was limited to energy consumption in producing plastic parts. The result of their study showed that specific energy consumption (SEC) during AM process was about a 100-fold compared to the conventional methods. Despite the high SEC of AM the study indicates that the use of material is more efficient in AM than in machining and injection molding. (Yoon et al., 2014).

2. Aim and purpose of this study

Aim of this study was to 1) determine the benefit of LAM on sustainability gains in terms of supply chain and 2) offer a methodology to conduct LCI analysis of the LAM and CNC machining. The supply chain benefits were studied by building possible supply chain scenarios for CNC machining and LAM. The building of these scenarios serve a base for a more in-depth analysis. The purpose of the building of the framework for practical test was to identify and characterize the different machine units and phases of each of the manufacturing processes to be able to ascertain their potential impact to efficiency.

Purpose of this study was to examine, how value chain in LAM from the raw material acquisition to the end user could be improved based on imaginary case study. The motivation was also to characterize LCI of LAM.

The purpose of the study was to find out what factors affect the sustainability of LAM and what elements can be measured in LCI as determinates of sustainability.

3. Methodology

The methodology used in this study were supply chain scenarios based on assumptions and experimental tests. Case models were created to examine the movement of raw material until final parts delivering to end users. A further analysis with practical test was carried out for LCI study.

In view of the supply chain, models were designed to include the transportation links among some key performers. The stages considered for the supply chain modelling started with transportation of raw material through to the end user without any pre or post activities.

In performing the LCI studies, it was necessary to limit the collection to one of the stages in the value chain of both processes. The production phase of both methods were selected as it involved actual fabrication of part. The procedure used to collect energy and raw material consumptions were carefully selected to agree with the standardized unit process LCI methodology, CO_2PE! Initiative!. This method was followed as a guide to perform the energy and material measurements. Figure 2 presents the steps included in the CO2PE! UPLCI Initiate.

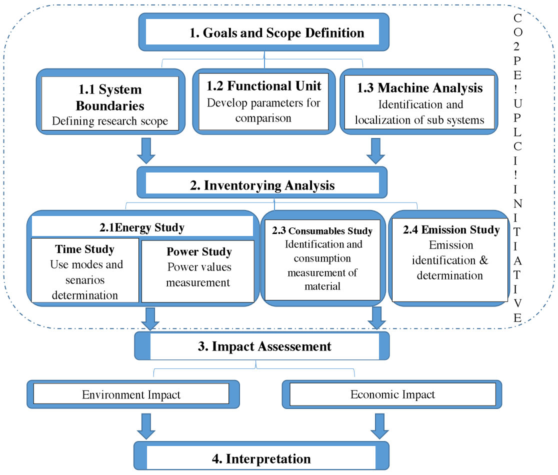

Fig. 2. Representation of systematic methodology for LCI study redrawn from (Kellens et al., 2012).

4. Experimental set-up

4.1. Data and assumptions for supply chain

The comparison of the supply chains for the two manufacturing processes were established by considering their configurations. Three assumptions were made in relation to these scenarios:

- It was assumed that supply chain starts from the steel bar for traditional process and powder for LAM process leaving out the ore extraction and atomization process.
- It was also assumed that customers will have a possibility to order parts from manufacturing companies directly. This implies that customers are not building parts even though it is feasible for large scale companies to acquire building unit.
- Lastly, it was assumed that raw material in both scenarios may be acquired locally from place of production. Transportation of raw material to production sites will be local.

4.2. Data and procedure used for LCI

The prerequisite for performing the LCI were to define the scope and goal of the study as well as parameters to be studied, functional units, system boundaries and phases to be included in the study.

In this study some assumption were made in order to ease the amount of data coverage. There could be several parameters and levels of manufacturing as well as functional units to be measured during an LCI analysis in a manufacturing process. As such simplifying or describing limitations of the study is important. The experimental part of this study was limited to production phase of both examined processes within a very narrow confinement. In order to characterize LCI of both LAM and CNC machining, numerical values were needed to quantify amount of energy and raw material used and the waste generated during the production phases. According to the methodology data could be measured, calculated or estimated based on experimental or literature studies. This study used measurements to investigate the material and energy consumption for the LCI studies.

5. Results and discussion

5.1. Supply chains

Conventional manufacturing: Figure 3 shows the hypothetical supply chain model created based part acquisition using the conventional (CNC machining) method.

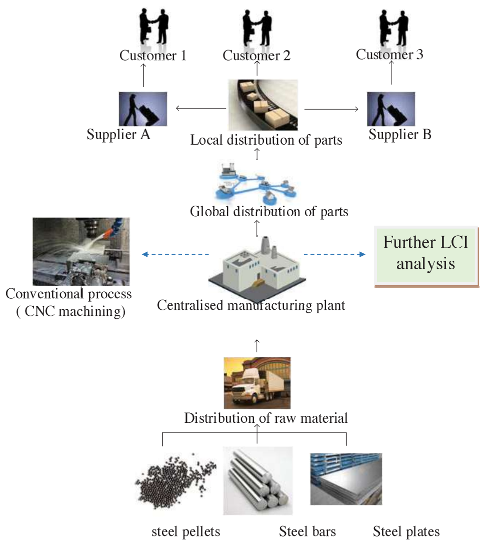

Fig. 3. Supply chain for conventionally manufactured part.

As it can be seen from Figure 3, the conventional model includes several intermediate steps in delivering products to end users. Aside these transitional steps, there could still be further delays as a results of the numerous process stages that may be needed in the fabrication stage. These may be as result of tools and fixtures installations or trail test in the case of machining. The process flow from bottom to up (see Figure 3) shows steel preforms are conveyed to manufacturing centre where machining of final parts are carried out.

The inclusion of local suppliers that may require stocking of parts was included with the aim to offer quick responds to orders and meet deadline of customer. This expatiate the supply chains and may also cover larger floor space as warehousing. As more often than not, a stocking of finished parts are kept both at the factory floors and in centralized distribution station where end users may order parts directly from or through local distributors. These form of logistics of finished parts often subject customers and companies to further labour and financial burden as extra cost and activities may be incurred.

LAM: The supply chain model of LAM depicts procurement phases between companies and end users. The mode of business may be direct or indirect using the service of middlemen. Figure 4 is an illustration of the supply chain of laser additive manufacturing for a stainless steel part.

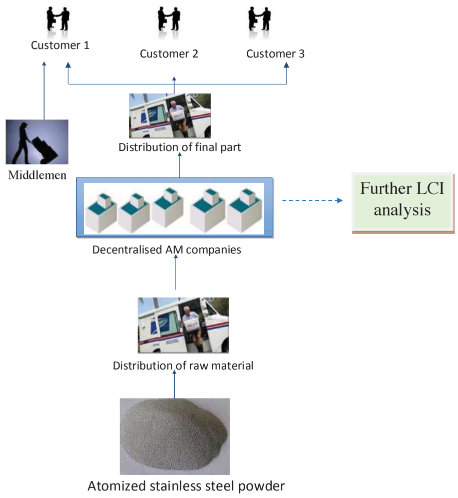

Fig. 4. Supply chain for laser additive manufactured part.

As it can be noticed from Figure 4, smaller space may be needed for production in LAM workshops and may create job opportunities as it supports decentralization. LAM has the advantage of producing parts closer to the market and has the potential to transform the supply chain to be more dynamic in manufacturing sectors. This presumes that the labor trading consideration for outsourcing may be reduced or eliminated. This may reduce lead time, cost and reduce rate of supply chain management risks significantly.

Land use with storage in LAM might be minimum as there is no need for stocking for either preforms (bar, pellets or plate) or finished products as required in conventional manufacturing methods such as CNC machining. In contrast, products can be built on demand in LAM.

The utilization of currier service in LAM shows that special schedules are not needed for distribution as raw material in the form of powder and finished parts are easily handled through normal post.

A significant reduction of lead time, cost and risk to the supply chain is thus achievable with LAM. These enhancements are not only feasible in manufacturing activities because of the replacement of carriage and inventory but also with the efficiency during the in-process chain in building parts on production level.

New designs from customers or size specifications can be incorporated into already stored data on a computer and printed layer by layer with just few steps without a need of a human presence in the production stage.

Companies may be offered the possibility to circular economy as generated chips from competitive process like CNC machining may be re-used in other AM processes, like direct energy deposition (DED) with only mechanical grinding to crush chips into desired grain sizes (Salminen, 2015). By so doing, SEC to produce metallic power from virgin material may also be reduced which highlights sustainable gain (Soukka, 2015).

5.2 Life cycle inventory

The outcome of the application of the systematic methodology CO2PE! UPLCI Initiative in this study are as presented in this session.

System boundary: In performing the LCI for the study, the scope in which research was carried out were defined as shown in Figure 5.

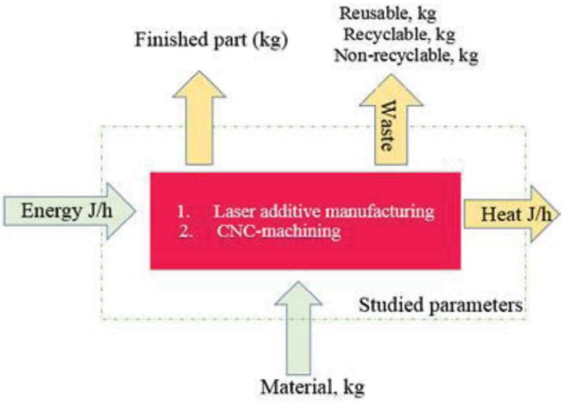

Fig. 5. Representation of system boundary.

As it is can be seen from Figure 5 the system boundary used in this study considered the amount of input and output energy and materials within manufacturing process.

Machine analysis studies: In order to carry out the LCI analysis it was important to define the machine tools and levels of the process to be studied. A primary selection of machine tools and levels to be investigated was necessary prior to the analysis. This step of the systematic LCI method allowed effective identification of energy and resource consuming units and their possible subsystems. The machine levels selected for CNC machining and LAM in this study are as shown in Figures 6a and 6b respectively.

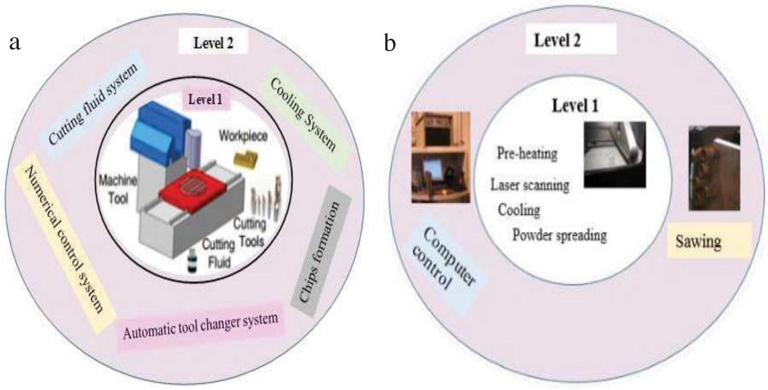

Fig. 6. Representation of a) CNC machining b) LAM levels analysed.

As it can be noticed from the Figures 6a and 6b, two levels of production in CNC machining and LAM were included in this study. The power values of energy driven elements were considered for energy consuming units (ECUs). Components such as such automatic tool changer, spindle motors, rotating tools and cutting fluid motor were considered for CNC machining. The ECUs in LAM on the other hand included heating units, laser and its cooling unit, servo, scanners and lightening system. Material inputs and outputs in various levels shown in Figure 6a and 6b were used to analyse material consumption in this study. The second level elements were studied as they complemented the finishing of production. Defining and selecting these elements was necessary as indicated in the methodology. Machine systems outside of these levels were not considered during LCI study. For instance energy consumed in lighting the production centre or conveying parts to machining centre were not considered as ECUs.

Geometry of work pieces: In this study practical tests were carried out with varying designs which included measure of degree of manufacturing flexibility and weight reductions. A modified research machine representing EOS EOSINT M-series was for LAM parts and a PUMA 2500Y multi axis lathe for CNC machined parts. Three test samples were designed as sample A, B and C for the experimental study. Samples A and C were designed to be produced with LAM only whereas sample B was planned to be produced with both CNC machining and LAM. Dimensions of the work pieces were 20 x 40 x 35 mm and an internal hole with a diameter of 24 mm. The models A and C were used as one of the criteria to affirm complexity and flexibility in LAM while sample A, B and C offered bases to compare resource and energy consumption for both processes. Geometry of test pieces used in the practical studies are as shown in Figure 7.

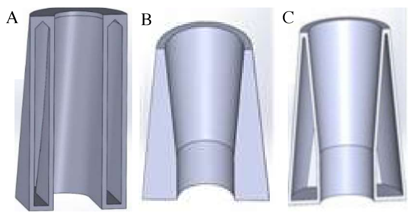

Fig. 7. Solid and cross sectional views of samples A, B and C used in this study.

As it can be seen from Figure 7, the models were designed to have solid and hollow walls. It was for instance only practicable to produce models B with CNC machining as the method was limited by the sharp edges in sample A and also the hollow wall in sample A and C. The internal geometry of sample A had sharp corners, hollow wall and a chamfered outside geometry. In order to have hollow walls in final parts of samples A and C there were 2 mm passage holes incorporated into design to remove excess powder after building. These features were included into designs in order to increase complexity of final products.

6. Conclusions and further studies

Aim of this study was to 1) perform comparative study of the supply chain configurations of LAM and CNC machining and 2) offer a methodology to conduct LCI analysis of the LAM and CNC machining.

This study has outlined how supply chains in LAM are improved with a modelled scenario based on marginal assumptions. The benefit might be true in practical cases as procurement management were improved with these models. Further studies however are needed to ensure the exactness of this benefit of agile supply model.

It was noticed that factors such as materials consumption, manufacturing steps, length of supply chain as well as swiftness of production affect the sustainability of a process. The production phase of LAM was identified to give a better sustainable gains in terms of material efficiency. However this cannot be said to be the only phase of sustainable gains as other phases were not included in the LCI study. In this study materials were measured as main determinates of efficiency.

In future, it would be imperative to examine the supply chain and LCI of LAM based on a practical use case. It may also be beneficial to broaden the scope of boundary to have a wider view of the material and energy efficiency offered by LAM by conducting a full life cycle assessment. It will be a notable undertaking to study the degree to which these parameters affect sustainability in LAM in further studies.

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Publication II

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Preliminary investigation on life cycle inventory of powder bed fusion of stainless steel

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Preliminary Investigation on Life Cycle Inventory of Powder Bed Fusion of Stainless Steel.

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Abstract

Manufacturing of work pieces from stainless steel with laser additive manufacturing, known also as laser sintering or 3D printing may increase energy and material efficiency. The use of powder bed fusion offers advantages to make parts for dynamic applications of light weight and near-net-shape products. Due to these advantages among others, PBF may also reduce emissions and operational cost in various applications. However, there are only few life cycle assessment studies examining this subject despite its prospect to business opportunity. The application of Life Cycle Inventory (LCI) in Powder Bed Fusion (PBF) provides a distinct evaluation of material and energy consumption. LCI offers a possibility to improve knowledge of process efficiency. This study investigates effect of process sustainability in terms of raw material, energy and time consumption with PBF and CNC machining. The results of the experimental study indicated lower energy efficiency in the production process with PBF. This study revealed that specific energy consumption in PBF decreased when several components are built simultaneously than if they would be built individually. This is due to fact that energy consumption per part is lower. On the contrary, amount of energy needed to machine on part in case of CNC machining is lower when parts are done separately.

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Keywords: energy efficiency; life cycle assessment; sustainability; specific energy consumption

1. Introduction

Additive manufacturing (AM), known commonly also as 3D printing, is nowadays coming more popular way of fabricating products as development of the technology from building prototype parts to functional parts has increased remarkably in 2000s. AM consist of seven different subcategories of different technologies. One of these technologies is powder bed fusion (PBF) of metallic materials. This technique is used to manufacture parts out of

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metal powder layer by layer by melting metallic powder by laser beam. Metal additive manufacturing has become popular in the aerospace, automotive, defense and medical industries according to Cooper et al. (2012) and Song et al. (2015) due to its many advantages over traditional manufacturing techniques, such as casting and stamping. Additive manufacturing allows automatized rapid prototyping and small series production of complex geometries and shapes. Additive manufacturing enables also the manufacturing of light weight components, which may include e.g. lattice structures. The manufacturing parameters in the additive manufacturing process can also be easily modified which allows rapid design changes as discussed by Santorinaios et al. (2006) and Yap et al. (2015).

However, there are only few studies published about the sustainability of the metallic AM process as most of the studies available have concentrated on polymeric materials. Due to aforementioned reasons this study is concentrating on measuring and analyzing of energy and material consumption in powder bed fusion of metallic materials. Main method in this study is life cycle inventory (LCI).

Nomenclature

AISI	American Iron and Steel Institute
AM	Additive manufacturing
ASTM	American Society for Testing and Materials
CO2PE!	Cooperative Effort on Process Emissions
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PBF	Powder Bed Fusion
SEC	Specific energy consumption
STL	Standard tessellation language

1.1. Sustainable manufacturing

Sustainable manufacturing and services oriented business models have become vital in various industrial sectors. Two important strategies to reduce the environmental impacts of manufacturing are energy efficiency and material recycling. Gutowski et al. (2013); Department of commerce (2015). Companies seek for energy and material efficiency processes with the aim to reduce cost of raw material, production, labor and energy. Reduction of storage, transportation and waste within industrial activities are other approach to reduce management costs (Rademaekers et al. (2011).

Allwood et al. (2011) have suggested options to improve material efficiency. These are for example longer life span, more intense use, repair and re-sale, product upgrades, modularity and remanufacturing, using less material to provide the same service. The study also concluded that still open questions will be which products, sectors and consumers are most appropriate for each of these strategies and what are the key trade-offs crated by usage of material efficiency strategies. The authors of this paper feel that additive manufacturing, and moreover powder bed fusion of metallic materials, could provide solutions for these questions. For example, ability to produce light-weight structures as one certain feature is seen very promising in this context. This paper will provide analysis of sustainability of PBF and conclude what added value this technology will provide.

Bourhis et al (2013) presents a strategy to evaluate the environmental impacts of additive manufacturing based on a predictive model. They conclude that it is important to include all flows and not only energy consumption, in the impact assessment. Nyamekye et al. (2015) conducted a study were powder bed fusion and CNC machining based supply chain model were compared. The results indicate that the use of AM offers possibilities to reduce downtime in supply of spare parts and reduce part inventory. This was a preliminary study and the environmental benefits of the AM based spare part supply chain were discussed but not verified by calculations.

1.2. Impact of PBF and CNC machining

Baumers et al. (2011) have presented specific energy consumption (SEC) of different AM systems. The studied systems included both laser beam and electron beam based additive manufacturing techniques. This study indicated that potential energy efficiency enhancements were possible by using high capacity utilization in PBF. This means that whole building area in AM machines is used. The study also shows that environmental impacts may be decreased in PBF during production.

Yoon et al. (2014) have similarly published a review on polymeric and metallic and a case study on polymeric AM methods, and also on traditional manufacturing technologies, injection molding and machining (e.g. milling and drilling). The case study was limited to energy consumption in producing plastic parts. The result of study by Yoon et al. showed that SEC in AM process were higher compared to injection molding and machining methods. This result was for AM of plastic materials, and as there is only small amount of heat present in AM of plastic material and plastics do not conduct heat, these technologies cannot really be compared in reliable way to other AM methods. The variance of SEC may vary for different systems thus it cannot be generalized for all AM technologies as shown by Baumers et al. (2011).

Morrow et al. (2007) have shown in their study that metal powder, which is used to make products using laser, may be produced either from preformed plate or liquid metal. The process flow may begin with casted ingots of scrap and sponge or pig iron. The study has shown that making powder from preformed plates (indirect atomization) ends up to about 42.3 % higher SEC than making powder from molten metal (direct atomization).

1.3. Life cycle assessment and CO2PE! UPLCI methodology

Life cycle assessment (LCA) can be determined as collection of environmental aspects and potential environmental impacts which relate with a product, service or production system throughout its life cycle ISO14040 (2006). LCA has been developed to produce scientific information about environmental impacts to help decision making processes for example in industrial companies. Cooperative effort on process emissions in manufacturing, CO2PE! Initiative offers a tool to study the material and energy flows systematically in existing and emerging discrete manufacturing processes. The methodology is based on ISO 14044 and ISO 14040 (2006) standards and is built to set a framework for the LCI phase of LCA for discrete manufacturing processes. A detailed description of the methodology is done by Kellens et al. (2012).

2. Experimental part

2.1. Aims of the study

The aim of the experimental part of this study was to:

- Carry out a life cycle inventory (LCI) of PBF and CNC machining
- Compare LCI of PBF and CNC machining and
- Investigate the effect of process variations on SEC in PBF and CNC machining.

The lifecycle inventory of the production phase was carried out as part of the study to:

- Identify the different phases in work flow of PBF and CNC machining and
- Measure the amount of input and output values of energy and material flows within each of these phases of PBF and CNC machining.

2.2. PBF and CNC machining process

The screening (without time study) and in-depth method (including time study) were used to collect all data needed on production phase of PBF according to CO2PE! UPLCI initiative methodology. Both measured and calculated data of PBF were used for the LCI studies.

- System boundary

The system boundary used in this study is as shown in Figure 1. The input and output data were monitored and reported accordingly for both PBF and CNC machining.

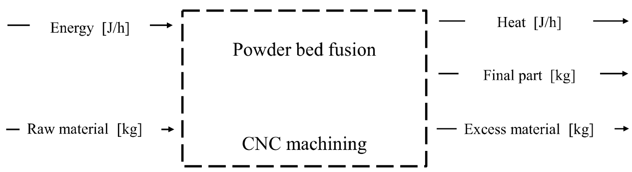

Fig. 1. System boundaries used for experiments in this study.

As it can be observed from figure 1, system boundaries were limited to analyze the energy and material flows of manufacturing phase. Data measured included power, time, inputs and outputs materials as well as auxiliary materials, like cutting liquids used in part removal phase. The energy consumption of material recycling was not included to the scope of the study since it focuses only to direct energy consumption during the manufacturing process.

- Machine analysis studies

A primary selection of machine tools and levels to be studied was defined as a guide to this study. The machine levels selected for PBF and CNC machining in this study are as shown in figure 2.

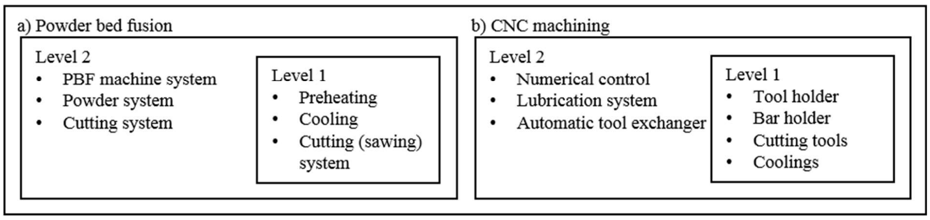

Fig. 2. Representation of machine levels selected for a) PBF and b) CNC machining.

As it is can be seen from figure 2, the sub systems selected for the energy analysis were limited to the direct production phases. Units, which were excluded from this study, were post-processing phases, such as removal of work pieces and also secondary units, such as lightning and air condition of fabrication room.

2.3. Material used in PBF

The stainless steel powder used for PBF was EOS Stainless Steel 316L powder. This steel powder has similar chemical composition as ASTM F138 ("Standard Specification for Wrought 18Cr-14Ni-2.5Mo Stainless steel Bar ASM International (2014)). The layer thickness is 20 µm and thinnest wall which can be achieved is about 300 to 400 µm. The building orientation for the parts determine tensile strength which is between 640 ± 50 MPa in horizontal (XY) direction and 540 ± 55 MPa in vertical (Z) direction. EOS (2015). Products, which are built from stainless steel, can be used in high temperatures and in corrosive atmosphere. EOS (2014).

2.4. Material used in CNC machining

Material used for the CNC machining was stainless steel of AISI 316L (EN 1.4404). This steel grade has high amount of molybdenum, which increases the overall corrosion resistant properties. AISI 316L has also high strength, good corrosion resistance, good sterilizability and good weldability. This steel grade is widely used in industries such as food, medicine, oil and gas.

2.5. AM equipment system used in PBF

A modified research machine representing EOS EOSINT M-series was used to build parts in PBF test. This equipment is totally equivalent to commercial equipment, but has ability to vary parameters more freely. This machine has a fiber laser with maximum laser power of 200 W and wavelength of 1070 nm. Diameter of focal point was 0.1 mm.

2.6. Power and energy monitoring equipment used in PBF

Siemens Sentron PAC 3200 was used to record power and energy consumption. LabView program was also used to monitor energy profile as the process was on.

2.7. CNC machining equipment

Doosan Daewoo PUMA 2500Y 4 Axis CNC Turning & Drilling Centre with a Fanuc 18i –TB (turning and boring) controlling system was used for the CNC machining. This machining center used had a working volume of 2918 x 1775 x 2060 mm (height x width x length). Power consumption in CNC machine was recorded by measuring voltage used by CNC device. The recorded voltage (range -10V and +10 V) were converted to power values with an already existing modelled equation.

2.8. Experimental procedure

- Test geometries

Three different samples with different geometries were used in this study, see appendix B1. The digital models were designed to have solid and hollow walls. Dimensions of the work pieces were 20 mm x 40 mm x 35 mm (width x height x depth) and an internal hole diameter of 25 mm and 18 mm from opposite directions to merging point. The geometries A and C were planned to be built with PBF only as they were not able to be manufactured with CNC machining

- Powder bed fusion

Two pieces of each sample A, B and C (so totally six parts) were built simultaneously with PBF. The PBF process began by heating of platform to temperature of 80ºC. This is done in order to guarantee good quality for couple of first layers and also to attach work piece properly to building platform. Thermal distortion is possible in PBF, and for this reason proper attachment of work pieces to building platform is required. Metallic powder was weighed and fed to the container and STL file was loaded to the computer. The building process began sequentially in repeated order of (1) spreading of metallic powder, (2) melting of metallic powder by laser beam and (3) returning of recoater to lay next layer from supports structure. See appendix B2

- CNC machining processes

The machining of one part on the PUMA 2500Y 4 Axis CNC Turning & Drilling Centre required four different machining operations, namely turning, drilling, milling and cut-off. Temperature control and lubrication of tool tip of the system was achieved with a 150 l lubricant in a ratio 95 % to 5 % of water and oil (CIMStar 501-02 oil) for all carriages and spindle.
Reference run was done without tooling to see success of fabrication prior to machining the actual part. Machining of a part were performed sequentially with right tool changes from outside (a) turning; (b) drilling; (c) inside turning (d) inside turning finishing; (e) milling; (f) cut-off. See appendix B3.
The progressive phases of both PBF and CNC machining are largely categorized into three sub-headings as shown in Figure 3.

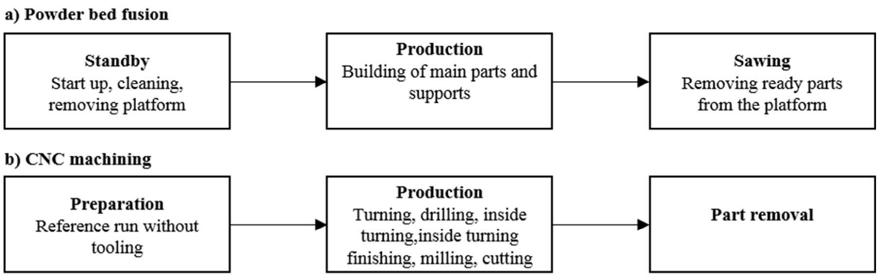

Figure 3. Representation of process sequence during a) PBF production and b) CNC machining

3. Results

3.1. Evaluation of energy and material usage

The use of both manufacturing processes to make the test pieces were characterized with some variation of energy and time. Thus the results represented in this study are based on the average of recorded values. Results of the energy and material flows analysis of the manufacture of the test pieces using PBF and CNC machining are shown in Table 1.

Table 1. Summary of energy and material consumption analysis of the studied methods.

Category	**Powder bed fusion**	**CNC machining**
Input (kg)	25.5 / 6 parts	0.71 / part
Output (kg)	0.56 / 6 parts 0.05 / 1 sample A 0.18 / 1 sample B 0.06 / 1 sample C	0.18 / 1 part
Re-usable powder (kg)	24.6	-
Metal bar or powder waste (kg)	0.34	0.53 / 1 part
Percentage of lost mass	~ 1.33	~ 74.6
Energy consumption (MJ)	~ 128 MJ / 6 piece 10.6 / 1 sample A 39.9 / 1 sample B 12.8 / 1 sample C	~ 3.24 / part

As it can be seen from the Table 1, the energy consumption estimated to build one part of sample B with PBF, 39.90 MJ, is greater compared to the amount, 3.52 MJ, used in CNC machining to produce the same comparable part.

A summary of energy, time and power values measured in the different modes of PBF are as shown in Table 2.

Table 2. Representation of energy, time and power values in PBF based on the platform utilisation.

Mode	Average power, P [W]	Time, t [s]	Energy, E [MJ]
Standby	562	1698	0.95
Heating	1380	530	0.73
Process / 6 pieces	1237	100980	125

The data presented in Table 2 summarizes the time and energy consumptions during the various phases of the building process during the production parts with PBF.

A representation of the average energy, time and power values measured in the different machining phases during the CNC machining experiment are as shown in Table 3.

Table 3. Representation of energy, time and average power values in CNC machining.

Process	Average power, P_{avg} (kW)	Time, $t_{process}$ (s)	Energy, E (MJ)
Outside turning	8.70	82.0	0.71
Drilling	6.89	19.0	0.13
Inside turning	6.92	101	0.70
Milling	3.05	477	1.45
Cut-off	16.6	11.0	0.18
Tool change	14.7	5.00	0.07
Total	56.9	695	3.24

Values in Table 3 are based on average power during the process. The power was measured with 1000 ms sample time.

3.2. Evaluation of energy and material consumption

Comparison of PBF and CNC machining based on the results of the inventory are presented in Table 4.

Table 4. System analysis of PBF and CNC machining.

Method	PBF	CNC machining
Form of raw material	Powder	Bar
Percentage of lost mass	1.00	75
Energy consumption (2 times each sample) samples	128 MJ (combined build 6 pieces)	3.24 MJ
Process residues	Metal chip, heat, cutting liquid	Metal chips, cutting liquid
Disposal of residue	Reuse, recycling, landfill	Recycling, landfill

As it can be seen from Table 4, PBF has higher material efficiency in the production phase as approximately 1 % of the input stainless steel powder was lost. Material loss in CNC machining was approximately 75 %. This result is very remarkable, as it suggests that material wastage is negligible in PBF during manufacturing phase. The amount of the steel removed as waste during machining is not a true representation from industrial manufacturing. This amount is greater as a result of the selected scope of study.

The energy consumed to fabricate sample B with PBF (39.90 MJ/sample B) is larger than when it is compared to (3.52 MJ/sample B) in CNC machining. PBF process had low consumption of electricity during fabrication phase (see Table 2).

3.3. Number of built parts vs. SEC in CNC machining and PBF

The energy consumption of PBF correspond to energy required to build corresponding number of parts whereas CNC machining represents sum of individual energy used to make parts separately. Number of built parts vs. SEC in PBF and CNC machining are as shown in figure 4.

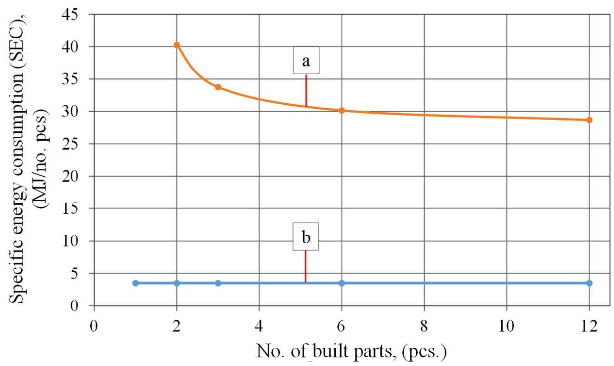

Fig. 4. SEC vs. number of parts in a) Powder bed fusion and b) CNC machining

The comparison shown in figure 4 is only valid for fabrication of part B. As number of built parts decreases in CNC, also fabrication energy consumed to produce one part increases. On the contrary, PBF process does not have any effect on this.

4. Discussion and conclusion

The results of this study indicated that energy usage in PBF was not increased by part complexity nor number of parts built. On the contrary, results found out in this study strongly suggests that CNC machining required same amount of energy to separately manufacture three pieces of sample B.

The result of this study shows that combined manufacturing with PBF might improve SEC.

The energy required to produce one part of sample B with PBF was approximately about 10 times higher (39.9 MJ) than the energy used in machine (3.52 MJ) comparable part. This indicates that the direct energy consumption of the production process is higher in PBF than in CNC machining. The material efficiency in PBF is enormous when compared with CNC machining. While approximately 74 % of input metal powder was utilized in the final part in PBF only about 25 % of starting bar were left as final part after machining.

Conducting a full LCA, cradle-to-grave, would be beneficial to understand the significance of the energy and material efficiency. For instance, the inclusion of the direct energy usage in metal bar or powder production phase and coolants. Also LCA case study from an application where the manufactured part influences the energy or resource consumption in the use phase would be essential in order to understand the sustainability of PBF technologies. The ability to design and manufacture geometries with PBF which have not been previously possible with any other conventional fabrication method provides interesting optimization possibilities for enchanted process properties in the use phase.

The production of discrete parts with PBF may offer high material and energy efficiency as the process gives high process control and flexibility during the planning stage of production when compared with the planning phase in CNC machining.

Acknowledgment

This study was carried out as a part of the Finnish Metals and Engineering Competence Cluster (FIMECC) program MANU - Future Digital Manufacturing Technologies and Systems, P6 Next Generation Manufacturing. Authors would like to thank all partners of this project. Authors would also like to acknowledge personnel of LUT Laser who assisted during execution of this study.

Appendix A. Material composition

Table 5. Alloying composition of EOS StainlessSteel 316L powder EOS (2015).

Alloying elements	Content of component, (%)	Alloying elements	Content of component, (%)
Chromium	17.5 -18	Copper	0.50
Molybdenum	2 .25 - 2.5	Manganese	2.00
Carbon	0.03 (maximum)	Silicon	0.750 (maximum)
Nickel	12.5 -13.0	Nitrogen	0.10
Sulphur	0.01 (maximum)	Iron	balance
Phosphorus	0.03 (maximum)		

Table 6. Alloying composition of stainless steel 316L bar.

Alloying element	Chromium	Molybdenum	Carbon	Nickel	Iron
Content of component, (%)	16.5-18.5	2 .25-2.5	0.03 (maximum)	10.0-13.0	balance

Appendix B. Representation of sample models

B.1. The Figure 1 shows digital models of these geometries.

The Figure 1 shows digital models of these geometries.

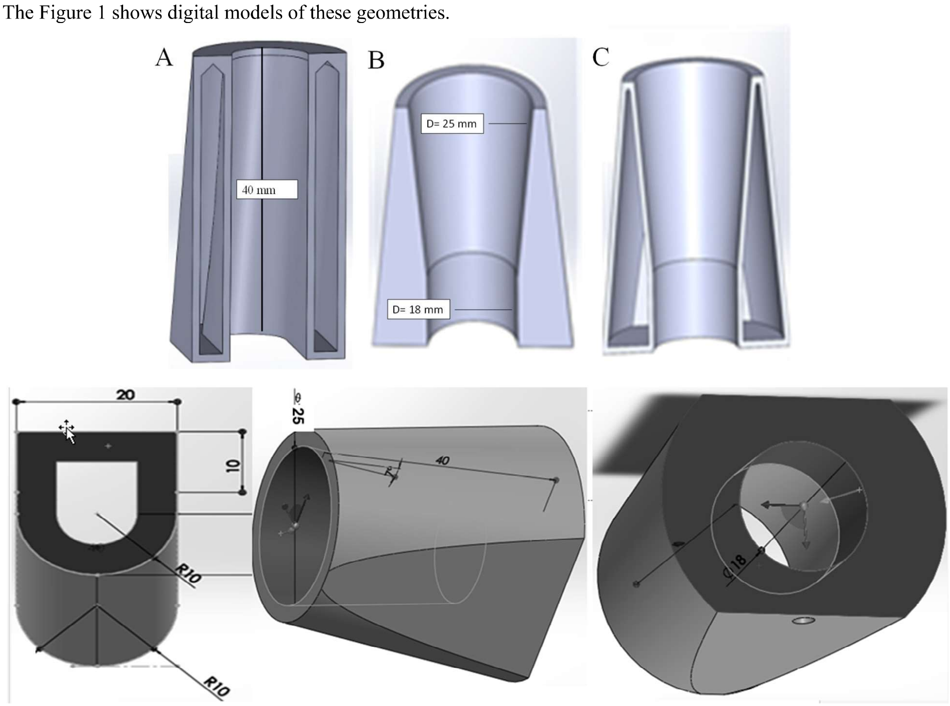

Figure 5. Cross sectional and 3D models of samples (a) A; (b) B; (c) C used in this study.

B.2. Representation of PBF manufacturing sequences

The Figure 6 shows the platform utilization which were used to estimate building time.

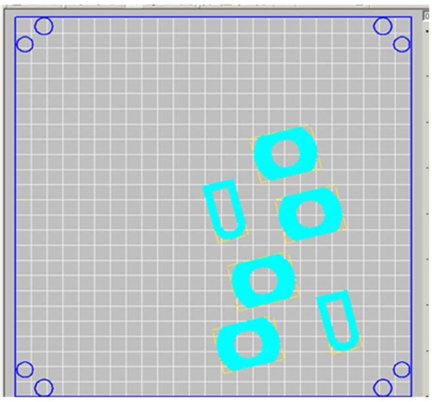

Figure 6. Representation of used platform utilization with two pieces each of sample A, B and C.

Phases of PBF manufacturing.

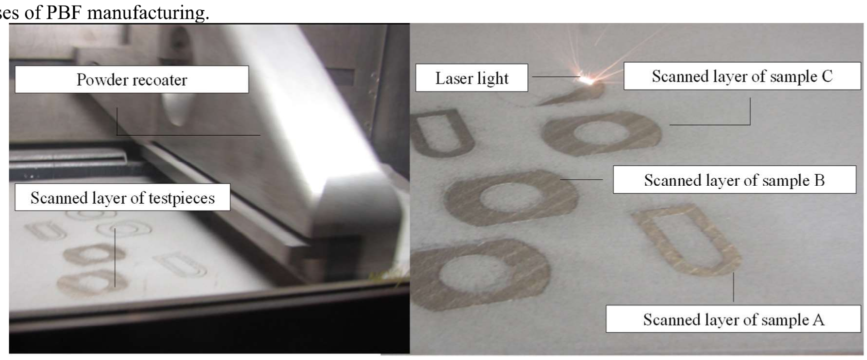

Figure 7. Representation of building phases during PBF. On the left picture powder recoater and on the right building of samples A, B and C simultaneously.

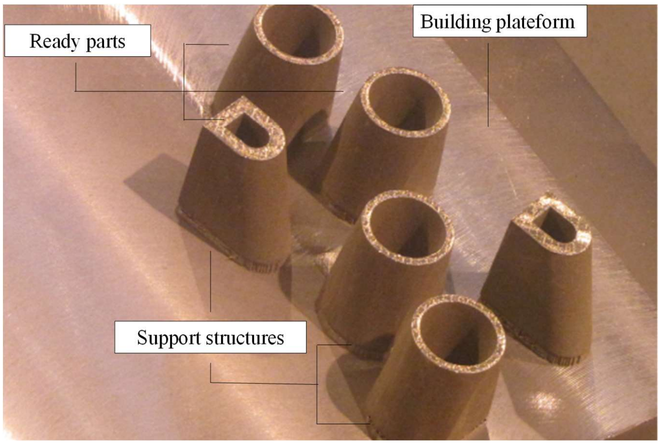

Figure 8. Representation of ready parts attached to building platform in PBF.

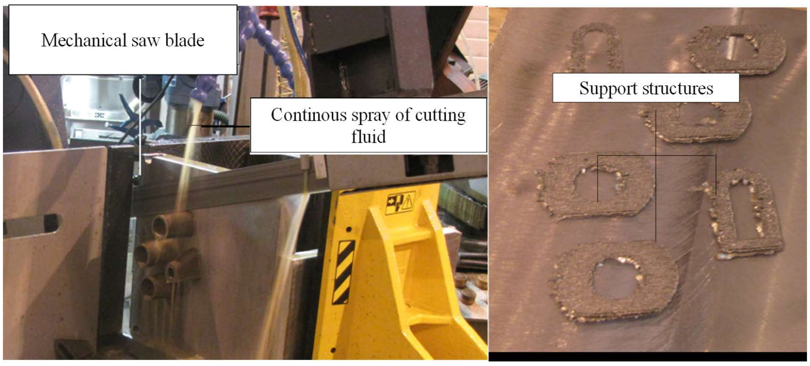

Figure 9. Representation of removal of test pieces from building platform in PBF.

B.3. Simulation of CNC machining sequence

Stock planning: Green sessions show stock prior to machining.	Phase 1: Rough and final turned outer surface shown in pink and orange respectively.	Phase 2: Drilled holes shown in yellow.

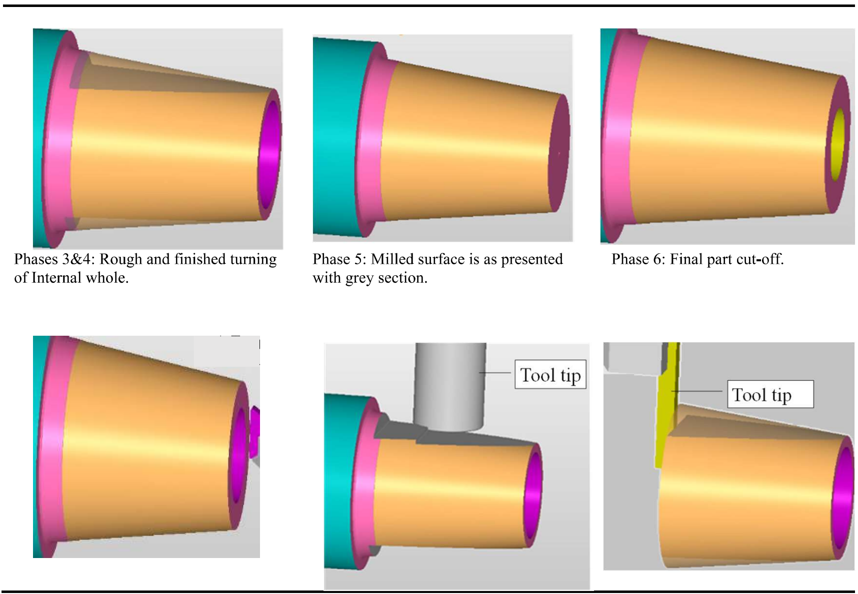

Figure 10. Representation of stock planning and the different machining phases.

The resultant of all phases during the CNC machining are as shown in Figure 10. Five tool changing were required to complete each test piece.

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Publication III

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Effect of process parameters on the formation of single track in pulsed laser powder bed fusion

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Abstract

There has been increasing interest in Laser Powder Bed Fusion (L-PBF) of metallic materials as a promising manufacturing technology. Although most L-PBF systems utilize laser beams with continuous wave emission (L-PBF(CW)), the possibility of using pulsed lasers (L-PBF(P)) has become available in some industrial L-PBF machines over the past few years. Previous studies suggest that the use of pulsed lasers could enable larger control of heat input and melt pool formation during the process, and could thus enable improvement of spatial resolution and feature sizes in L-PBF. In this study, the experiments were implemented using a pulsed laser in combination with continuous scanning movement instead of the 'point-and-shoot' method typically used by industrial L-PBF(P) machines of today. The experiments were executed using a trial L-PBF system (IPG ytterbium fiber laser, wavelength 1075 nm) for gas-atomized stainless steel 316L powder on compositionally similar substrates. Single tracks were melted with three different pulse lengths (50, 100, and 200 µs) by using a constant layer thickness of 50 µm, while varying pulse repetition rate, scanning speed and laser power based on six preset values of volume energy density (*VED*) of 36-120 J/mm^3. In order to allow a comparison to be made, additional samples were manufactured by using the CW emission of the same laser. It was observed that the L-PBF(P) samples yielded narrower tracks in comparison to the samples manufactured using CW emission. In addition, the results of the experiments show that, while maintaining constant *VED* values, decreasing the pulse length or scanning speed decreased the widths of the tracks and their penetration into the substrate. Consequently, it was noticed that shorter pulse lengths require more overlap between consecutive pulses in order to produce continuous tracks. Pulsed emission shows potential for improving the spatial resolution of the L-PBF process.

Peer-review under responsibility of the scientific committee of the 17th Nordic Laser Material Processing Conference.

Keywords: Laser powder bed fusion; Additive manufacturing; Pulsed emission; Single track; AISI 316L

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1. Introduction

Laser Powder Bed Fusion (L-PBF) has become a widely used method for additive manufacturing of metallic materials in the past few years. Besides continuous wave emission (L-PBF(CW)), the advantages of using pulsed emission (L-PBF(P)) have been discussed in the scientific literature during the past decade [1-4, 6-14]. There has been discussion of the possible opportunities offered by pulsed emission in minimizing thermal distortions and increasing spatial resolution in L PBF due to the more controlled heat input and melt pool formation during the process. This is well illustrated by the previous efforts to manufacture thin wall structures from nickel base alloys with Nd:YAG based pulse lasers by [1-3] and from copper with femtosecond pulse laser by [4]. Laser pulses generated by these systems typically employ high peak powers compared to CW emission.

However, most of the current commercially available L-PBF systems utilize modern fiber lasers as the primary heat source for melting [5]. This provides large possibility for feasible process integration for pulsed lasers with modern L-PBF systems, since most fiber lasers can be pulsed by fast power modulation down to the lower microsecond range with pulse repetition rates up to multiple kHz while employing comparable peak powers to those of CW emission [6]. Although most currently available L-PBF systems utilize a laser beam with CW emission, pulsing laser by power modulation has already been implemented in commercial L-PBF systems manufactured by Renishaw [6]. These systems typically employ the power modulated lasers with so-called 'point-and-shoot' method, which allows the system operator to select the distance between consecutive laser pulses.

Previous scientific research on power modulated L-PBF systems has primarily focused on utilizing this method for the fabrication of various alloys by L-PBF, as studies on aluminum alloys by [7-9], nickel base alloys by [10], and titanium alloys by [11-12] demonstrate. In addition to microstructural advances, it was shown experimentally by [13] that while the same amount of volume energy density (*VED*) was applied for both L-PBF(P) and L-PBF(CW) processes, the samples manufactured using L-PBF(P) exhibited narrower tracks. In fact, recent studies by [8, 13-14] indicate that power modulated L-PBF(P) may allow improvement of the spatial resolution of the process, which could enable enhancement of accuracy and in-situ manufacturing of finer features in L-PBF. This possibility was the main motivation for conducting this study.

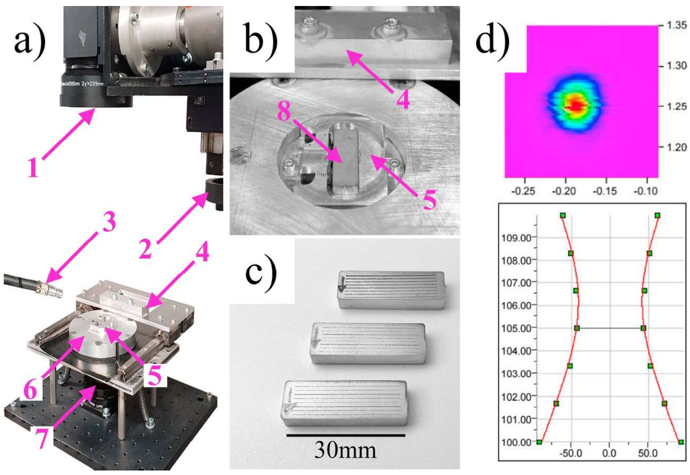

Fig. 1. (a) The in-house developed L-PBF system; (b) Adjustable build platform system of the L-PBF setup; (c) Three patches of produced single tracks on substrates; (d) Measurement of used laser beam by Primes MicroSpotMonitor. Numbering of the components in the figure: (1) focusing optics, (2) adjustment of the focal point position in z-direction, (3) argon inlet, (4) manual powder re-coater system, (5) build platform with a screw-tightened slot for detachable substrate pieces, (6) build platform frame, (7) adjustment of the substrate position in z-direction, and (8) detachable stainless steel substrate piece.

The aim of this study is to investigate the formation of single tracks in L-PBF(P) to understand general process phenomena and the effects of associated process parameters, and to characterize the resulting feature sizes in order to understand the potential of pulsed emission in improving the spatial resolution of L-PBF. This study also aims to identify the optimal processing conditions to support future investigations on manufacturing of fine-featured objects, such as thin walls, with the L-PBF(P) setup described in the experimental section of this study.

2. Experimental setup

2.1. L-PBF system

Fig. 1 shows the in-house built trial L-PBF system that was used for the experiments in this study. The L-PBF system consisted of an IPG ytterbium fiber laser (wavelength 1075 nm, maximum average power 200 W) and a manually operated build platform system with a screw-tightened slot for ~5x10x30 mm^3 detachable substrate pieces. The repeatability of the powder layer deposition from patch-to-patch in the experiment was ensured by a delicate mechanical calibration of the substrate surface and re-coater blade before the deposition of each patch.

The laser produced a beam with a near Gaussian power distribution and a focal point diameter of ~82 µm with a Rayleigh length of 3.24 mm, as measured by Primes MicroSpotMonitor monitoring tool (Fig. 1d). For the experiments, the laser was power modulated by a frequency generator. With the described setup, the maximum modulation frequency of the laser was 2 kHz. Based on initial test results, the laser pulses produced by the system were near square shaped with short power rise and fall times (~10 µs).

2.2. Materials

Gas atomized stainless steel 316L powder was used for the experiments. The volume-weighted particle size distribution (Fig. 2a) of the used powder was measured using an automated optical imaging system (Morphologi by Malvern Panalytical Ltd) with a particle size measurement range from 1 to 1000 µm. As shown in Fig. 2b, scanning electron microscope (SEM) based analysis of the powder revealed that it consisted predominantly of spherical particles, although some irregularities were observed.

The single tracks were deposited on ~5x10x30 mm^3 stainless steel 316L substrates that were laser cut from cold rolled sheet metal. After cutting, the edges of the substrates were refined using a grinding wheel to allow facile functioning of the powder re-coater during sample manufacturing.

The compositions of the used powder and substrates were measured using energy dispersive x-ray spectroscopy (EDS) and are shown in Table 1. EDS analysis revealed that the composition of the substrates deviated from the standardized 316L composition, as shown by an excessive amount of chromium and insufficient amounts of nickel and molybdenum. The composition of the powder was within the limits set by standardization. Since the observed compositional differences were small, they were estimated to have only a marginal effect on the results of the study.

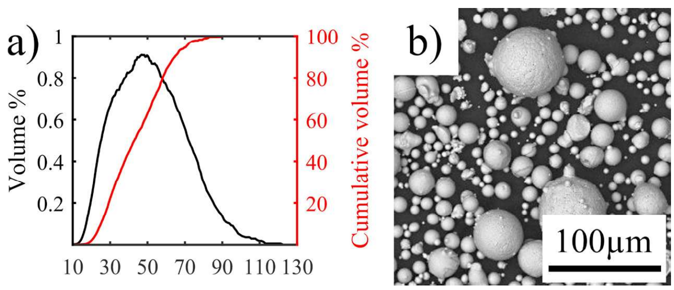

Fig. 2. (a) Volume-weighted particle size distribution of the gas-atomized 316L powder: $d_{0.1}$ = 25.1 µm, $d_{0.5}$ = 42.8 µm, and $d_{0.9}$ = 64.5 µm; (b) Scanning electron microscope (SEM) image of the gas-atomized 316L powder.

Table 1. Measured compositions of the used substrates and powder in wt.%. Relative accuracy of the measurement was 5%.

Sample	Si	Cr	Mn	Fe	Ni	Mo
Substrate	0.6	19.9	1.8	69.5	7.6	0.6
Powder	0.4	16.4	1.1	68.5	11.3	2.3

2.3. Process parameters

In this study, the experiments were implemented using a pulsed laser in combination with continuous scanning movement instead of the 'point-and-shoot' method common in industrial L-PBF machines of today. For this purpose, the theory of pulsing was adapted from previous scientific efforts on L-PBF(P) by [13-14] and pulsed laser welding by [15-16]. The average laser power (P_{avg}, W), volume energy density (*VED*, J/mm^3), and pulse overlap (O_p, a.u.) for the L-PBF(P) process were calculated using Equations 1-3.

$$P_{avg} = f \cdot P_{peak} \cdot t_p \quad (1)$$

$$VED = \frac{P_{avg}}{d \cdot v \cdot t} \quad (2)$$

$$O_p = 1 - \frac{v}{f \cdot \left(d + v \cdot t_p\right)} \quad (3)$$

where f is pulse repetition rate (Hz), P_{peak} is peak laser power (W), t_p is pulse length (s), d is laser beam diameter on the surface of the powder bed (mm), v is scanning speed (mm/s), and t is powder layer thickness (mm).

The used process parameters for both L-PBF(P) and L-PBF(CW) samples are summarized in Table 2. For the experiments, single tracks of 25 mm in length were manufactured in 18 patches of nine tracks (total of 162 samples) leaving a 1 mm-wide gap between each track in a patch in order to avoid the influence of consecutive tracks on sample quality. Single tracks were melted for three pulse lengths (50, 100, and 200 µs) using a constant layer thickness of ~50 µm and a varying pulse repetition rate (1100, 1500, and 1900 Hz) and peak laser power (80, 135, and 190 W). The selection of the process parameters for the experiments was simplified by determining six constant values of *VED* (between 36 and 120 J/mm^3) which were maintained by adjusting scanning speed (9-489 mm/s) for each parameter combination.

In order to allow comparison, additional samples were manufactured using CW emission of the same laser in four patches of nine tracks (total of 36 samples) using a similar range of *VED* values while varying laser power and scanning speed. Equation 2 was used for calculating *VED* in the CW process because for CW process $P_{peak} \approx P_{avg}$. All samples were manufactured in an ambient temperature without substrate preheating in an inert argon atmosphere. The laser beam was focused on the surface of the powder bed during sample manufacturing.

Table 2. Summary of the used process parameters.

Parameter	L-PBF(P)	L-PBF(CW)
Pulse length (*µs*)	50, 100, 200	-
Volume energy density (*J/mm^3*)	36-120	36-120
Peak laser power (*W*)	80, 135, 190	30-190 (20)
Pulse repetition rate (*Hz*)	1100, 1500, 1900	-
Powder layer thickness (*µm*)	50	50
Scanning speed (*mm/s*)	9-489	49-1030

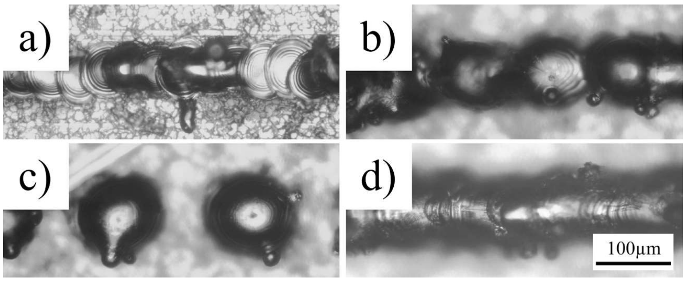

Fig. 3. Criteria for analysis of the deposited single tracks. (a) Insufficient melting; (b) Irregularity or insufficient necking of consecutive pulses; (c) No necking between the consecutive pulses; (d) Sufficient formation of continuous track.

2.4. Single track measurements and sample preparation

Preliminary inspection of the manufactured samples was implemented using an optical microscope in order to conduct qualitative analysis of the tracks. Based on visual appearance from above (perpendicular to the surface of the substrate), the tracks were divided into groups as presented in Fig. 3. In order to verify the results of the initial analysis, the manufactured samples (nine tracks per substrate on 22 substrates) were first cut from approximately the middle in length and then mounted into acrylic cold mounting resin (ClaroCit). Consecutively, the samples were ground incrementally using SiC abrasives and then polished using diamond paste (grain size 3 µm) and napless cloth. Polished cross sections were afterwards etched using 30 V dc voltage for 30 s in etchant solution containing 1 part oxalic acid and 9 parts H_2O. The prepared sample cross sections were inspected using an optical microscope in order to evaluate metallic bonding of the tracks into the substrates and to measure dimensions (track width and penetration depth into the substrate) of the prepared cross sections of the continuous tracks. The absolute accuracy of the measurement was 5 µm. Sample preparation and measurements were repeated three times to average the results.

3. Results and discussion

The results of the qualitative analysis of the tracks are presented in Fig. 4. It was noticed that all of the used pulse lengths exhibited a similar distribution of different track types (presented in Fig. 3, above) alongside the horizontal and vertical axes shown in Fig. 4. These distribution areas are marked in Fig. 4 using dashed lines as follows: 1) area of insufficient melting, where there was no noticeable metallic bonding between the track and the substrate; 2) area of sufficient melting of continuous tracks; and 3) area where the pulse overlap between consecutive pulses is insufficient to seamlessly connect the consecutive melt pools (when the overlapping value is decreased, further necking between the consecutive melt pools does not happen). Most samples in area 3 showed the typical sign of non-optimal pulsing that is vaguely visible as a small dark dot in the middle of each non-continuous section of the track in Fig. 3c.

As can be observed from Fig. 4, the level at which overlap becomes critical for single track formation (the dashed line that separates areas 2 and 3) appears to depend on the used pulse length. Based on the results of the qualitative analysis, in order to produce continuous tracks, samples manufactured using 50 µs pulses required ~0.55 or more overlap, samples manufactured using 100 µs pulses required ~0.25-0.35 or more overlap, and samples manufactured using 200 µs pulses required ~0.10-0.25 or more overlap.

Overlapping in L-PBF(P) is a generally well-understood phenomenon: assuming constant pulse length and diameter of the laser beam on the surface of the powder bed, increasing pulse repetition rate increases overlap and increasing scanning speed decreases overlap. As was well illustrated by [6], larger melt pools require less overlap in order to form continuous tracks in L-PBF(P). Thus, it is emphasized that differences in minimum overlap requirements with different pulse lengths may be at least partially explained by differences in melt pool volumes. Observations made from width and penetration depth measurements of the manufactured continuous tracks support this claim.

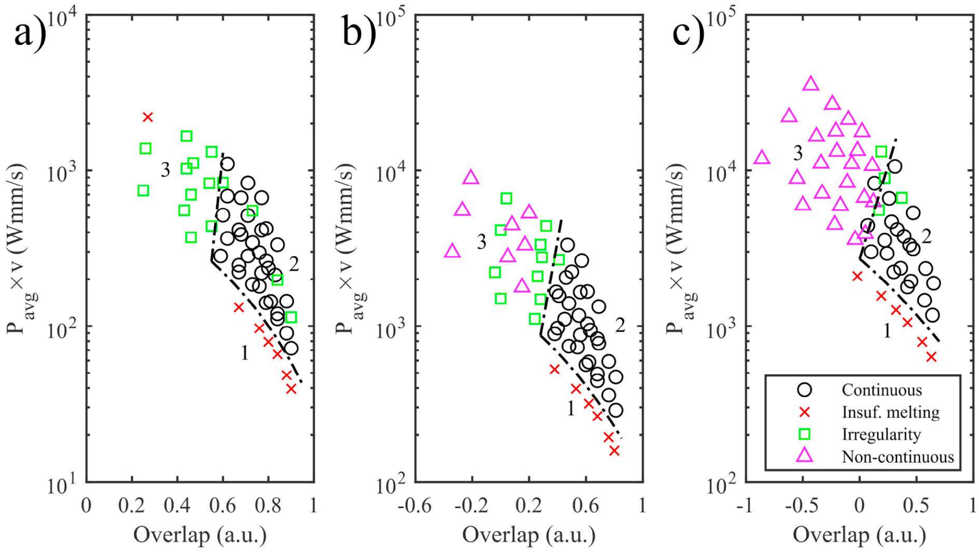

Fig. 4. Qualitative analysis of the manufactured L-PBF(P) samples. (a) 50 µs pulse length; (b) 100 µs pulse length; (c) 200 µs pulse length.

3.1. Track dimensions

The measured widths and penetration depths of the continuous tracks manufactured in this study are presented in Fig. 5 and summarized in Table 3. Overall, L-PBF(P) samples resulted in narrower tracks in comparison to the samples manufactured using CW emission, which corresponds to observations made by [14]. The results show that decreasing the pulse length decreased single track widths and resulted in smaller penetration into the substrate with the L-PBF(P) setup used in this study. The results support the claim that decreasing pulse length decreases the size of the melt pool, which can be observed as a reduction of the cross-sectional area of the tracks.

Table 3. Summary of the measured dimensions of the manufactured single tracks.

Parameter	Track width (µm)	Track penetration (µm)
L-PBF(P), *tp* = 50 µs	76-103	16-57
L-PBF(P), *tp* = 100 µs	85-132	15-79
L-PBF(P), *tp* = 200 µs	105-159	39-157
L-PBF(CW)	105-230	33-117

From the perspective of selection of process parameters for L-PBF(P), pulse length is a constraint to scanning speed due to the requirement of achieving a sufficient amount of pulse overlap, especially concerning the limitations set by the maximum pulse repetition rate (2 kHz) of the used equipment in this study. In addition, with shorter pulses, the laser energy is deposited in smaller quantities, which will evidently affect melt pool behavior because the melt pool will not solidify between pulses, but the consecutive pulses affect the same melt pool (estimated based on research by [17]). Overall, increasing pulse length seems to bring the L-PBF(P) process phenomenon closer to the CW process. Further research is required to understand the process phenomena occurring in single track, single layer and multilayer processes.

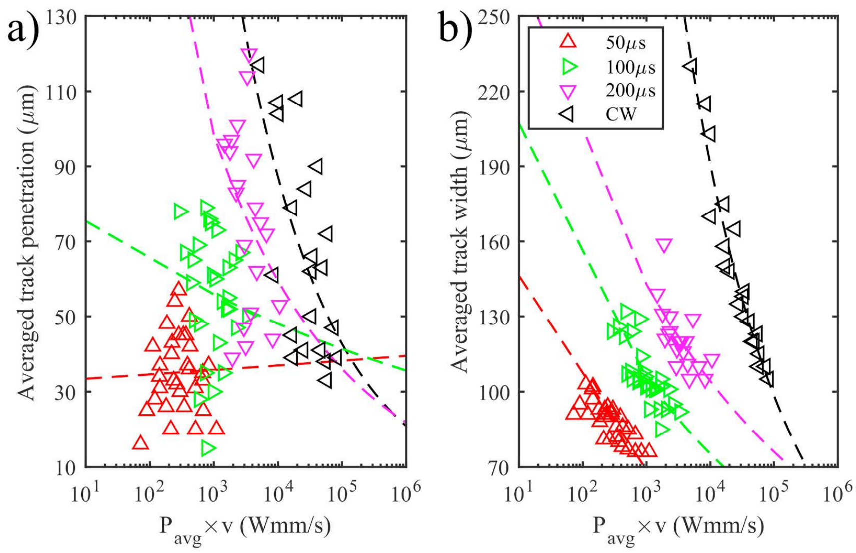

Fig. 5. (a) Measured track penetration depths into substrate; (b) Measured track widths.

In addition, the results show that while *VED* were maintained as a constant, increasing scanning speed lead to a decrease in track width with both L-PBF(P) and L-PBF(CW) processes. The same phenomenon was observable with measurements of track penetration depth, although there is more variation within the values. Although the same amount of energy was deposited for all samples with the same value of *VED*, each sample exhibited its own pair of applied average laser power and scanning speed. Generally, samples with higher average power exhibited higher scanning speeds in order to maintain a constant *VED* value, thus placing them on higher values on the horizontal axis of Fig. 5. Previous research by [14, 17] shows that besides the energy input of the process, melt pool geometry and dimensions are also largely affected by overall process efficiency and interaction time between the laser beam and the material, which is likely contributing to the observed phenomenon. In this study, *VED* was varied between six constant values, but the detected differences in track widths between different *VED* values were minimal. This was expected, because the used method of parameter selection distributed the samples with different *VED* values within each other in the presented data.

Fig. 5b shows that the track widths of the samples manufactured using 50 and 100 µs pulses saturated towards the used laser beam diameter on the surface of the powder bed (~82 µm), which indicates that laser beam diameter was a restricting factor for further reduction of track widths. Thus, it was emphasized that the resulting track widths could be reduced further by decreasing the size of used laser beam diameter, and by using powder material with smaller particle size distribution in thinner layers. However, consequently the process could become unpractical or unfeasible for integration with modern commercial L-PBF processes due to lost productivity. The observations made in this study support the claim that use of pulsed emission may improve spatial resolution of the L-PBF process.

4. Conclusion

The effect of process parameters on the formation of single tracks in pulsed laser powder bed fusion (L-PBF(P)) of stainless steel 316L was experimentally studied in this study. In the experiments, single tracks were melted for three pulse lengths (50, 100, and 200 µs) using a constant layer thickness of 50 µm, while varying pulse repetition rate, scanning speed, and peak laser power based on six preset values of volume energy density (*VED*) of 36-120 J/mm^3.

In order to allow comparison, additional samples were manufactured using continuous wave emission (L-PBF(CW)) of the same laser. The principal results of this study are as follows:

- It was shown that shorter pulse lengths require more overlap between consecutive pulses in order to produce continuous tracks. In order to produce continuous tracks, samples manufactured using 50 µs pulses required ~0.55 or more overlap, samples manufactured using 100 µs pulses required ~0.25-0.35 or more overlap, and samples manufactured using 200 µs pulses required ~0.10-0.25 or more overlap.
- L-PBF(P) samples resulted in narrower tracks in comparison to the samples manufactured using CW emission, thus confirming the observations made by previous studies. It was observed that decreasing pulse length in L-PBF(P) decreased resulting single track widths and resulted in shallower penetration into the substrate. In addition, it was observed that maintaining preset values of *VED* while increasing scanning speed decreased resulting single track widths and penetration depths for both L-PBF(P) and L-PBF(CW) processes.
- Pulsed emission shows potential for improving the spatial resolution of the L-PBF process. Further investigation is required to understand the process phenomena occurring in single track, single layer, and multilayer processes.

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Publication IV

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Integration of DfAM and LCC Analysis for Decision Making in L-PBF

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Review

Integration of Simulation Driven DfAM and LCC Analysis for Decision Making in L-PBF

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Abstract: Laser based powder bed fusion (L-PBF) is used to manufacture parts layer by layer with the energy of laser beam. The use of L-PBF for building functional parts originates from the design freedom, flexibility, customizability, and energy efficiency of products applied in dynamic application fields such as aerospace and automotive. There are challenges and drawbacks that need to be defined and overcome before its adaptation next to rivaling traditional manufacturing methods. Factors such as high cost of L-PBF machines, metal powder, post-preprocessing, and low productivity may deter its acceptance as a mainstream manufacturing technique. Understanding the key cost drivers of L-PBF that influence productivity throughout the whole lifespan of products will facilitate the decision-making process. Functional and operational decisions can yield profitability and increase competitiveness among advanced manufacturing sectors. Identifying the relationships between the phases of the life cycle of products influences cost-effectiveness. The aim of the study is to investigate the life cycle cost (LCC) and the impact of design to it in additive manufacturing (AM) with L-PBF. The article provides a review of simulation driven design for additive manufacturing (simulation driven DfAM) and LCC for metallic L-PBF processes and examines the state of the art to outline the merits, demerits, design rules, and life cycle models of L-PBF. Practical case studies of L-PBF are discussed and analysis of the interrelating factors of the different life phases are presented. This study shows that simulation driven DfAM in the design phase increases the productivity throughout the whole production and life span of L-PBF parts. The LCC model covers the whole holistic lifecycle engineering of products and offers guidelines for decision making.

Keywords: design for additive manufacturing; life cycle cost; metal; laser powder bed fusion; productivity

1. Introduction

Additive manufacturing (AM), known also as 3D printing, is "a process of joining materials to produce parts based on three-dimensional (3D) modelling, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. Aerospace, medical, automotive, and service bureaus are key sectors where AM continues to evolve with automotive leading in developments towards full-scale production of AM for benefits such as improved strength and weight functionality [2–5]. There has not been much precedence in assisting companies in integrating L-PBF to business portfolio, except for a few published studies concerning computer simulation software such as Autodesk, nTopology, SolidWorks, CATIA, E-Stage, and Magics [6–9]. The scarcity of available literature on the cost-efficiency and lacking reports from industrial scientific sectors currently limit AM industrial full implementation [10–12] as published data are often highly case-specific.

These challenges are possible to overcome once the key players involved in this modern technological milestone unveil the formation of costs and elaborate the scientific knowhow [13,14]. This paper aims to show how simulation driven design for additive manufacturing (simulation driven DfAM) rules may be utilized with attention to the effect on part quality and accompanying life cycle cost (LCC) to offer better understanding and aid in its adoption. The optimization possibilities for improved profitability and new research areas also are discussed. No study to our knowledge has considered an integrated study of simulation driven DfAM and LCC for cost efficiency.

The basis of this study is the role of simulation driven DfAM in metal L-PBF. This study intends to identify the influence of key cost drivers and processes that can be optimized to control LCC. In the current paper, simulation driven DfAM and LCC will be considered together with the life cycle phases that are susceptible to economic inefficiency of implementation of L-PBF. In addition, other advantages of L-PBF are addressed based on earlier industrial application. The integrated LCC method to L-PBF is presented to highlight the means to optimize energy and raw material consumption, generated waste volume, time, and overall cost throughout the life span of products.

1.1. Laser-Based Powder Bed Fusion

AM methods, including powder bed fusion (PBF) processes, start with the transformation of a 3D model file to STL-format to readable sliced layers for the machine system to machine setup [15]. These files are then exported for necessary modifications and selection of suitable process parameters using special software designed for that specific machine. After actual printing, the platform and built parts are removed from the building chamber and undergo detachment from building platform and subsequent post-processing, which typically involves polishing, coating, machining, or heat treatment according to requirements of the application [2,10,15–17]. PBF is an AM technique in which "thermal energy selectively fuses regions of a powder bed" [1]. PBF methods can be categorized into two sub-methods, all following the same layer-wise steps [18–20] to create parts as shown in Figure 1 [1,20].

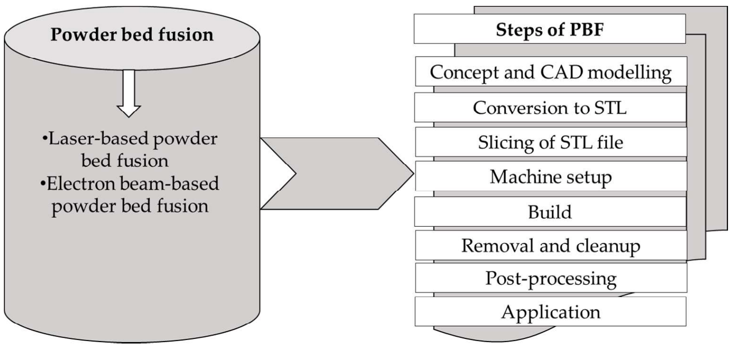


Figure 1. Schematic representation of powder bed fusion (PBF) systems and steps of manufacturing [1,20].

Figure 1 shows the hierarchy of the steps employed to build parts using PBF machine systems. The different can be difference in ways to achieve specific step for each of the building phase. For instance, L-PBF employs a powder reservoir whereas electron beam-based powder bed fusion (EM-PBF) a hopper to feed powder to the building platform. Different techniques of PBF offer advantages that are unattainable with comparable traditional manufacturing methods [6,16,18–21]. Some of these benefits include the creation of conformal flow channels, reduced manufacturing steps, lattice structures for improved weight, and stiffness. Laser-based powder bed fusion (L-PBF) is one of the subtypes of PBF used to produce structures from powder raw material with the energy of one or more laser beams that selectively melt and fuse the particles at the surface, layer upon layer, in an enclosed process chamber [22].

1.2. Merits and Demerits of L-PBF

L-PBF offers benefits such as manufacturing on-demand, shorter lead times, design flexibility, and ease of design modifications. The application of L-PBF and other AM methods has the potential to improve the existing inefficacies in manufacturing, especially regarding minimizing the amount of source material needed and produced waste [6,10,23]. L-PBF processes eliminate the auxiliary operational and the investment needs such as several manufacturing and assembly steps in different locations [24] and number of essentially needed molds and tools subject to traditional methods [25].

The ability to reduce component weight by creating a customized lattice, net-, and web-like metal structure [26] for L-PBF manufacturing makes the process suitable for dynamic application fields such as aerospace and automotive sectors. This is because all weight reduction improves functionality and thus improves fuel consumption efficiency during the whole service life of the parts [11,15,27–29]. Operational costs can be reduced through product design optimization for L-PBF with attention to specific material and equipment that is used to print the parts [30–32]. Increasing the throughput of a construction job with shorter lead times will increase productivity [33]. L-PBF costs are largely dependent on the design and manufacturing, therefore, these phases must be optimized in terms of part structural integrity and building process.

Most notably, L-PBF provides a cost-effective means to produce spare parts on time and demand and is usually geographically closer to the user. This reduces inventory and storing costs and simplifies the supply chains while improving the delivery times. Reducing the downtime by manufacturing or repair on demand can also eliminate unwanted costs during the service life of products. Prime examples can be found from the aerospace industry, where unexpected cancellation of planned flights leads to major losses in revenue and accumulation of indirect expenses. Large companies have often heavily invested in spare part acquisition and storage to eradicate or reduce such monetary losses in the occurrence of sudden breakdowns [29]. A major part of L-PBF costs do not have to account for the afore-mentioned aspects, as the price is largely dependent on processing time itself. Hence, any reduction in manufacturing time reduces the overall production cost and results in higher net profitability.

The most common factors discouraging the acceptance of L-PBF are the investment cost of metal L-PBF machine, price of metal powder, lack of standardization, validation, and limitations on the part size [10,34–36]. Lack of knowhow of potential of simulation driven DfAM has also a huge effect to this. Several studies [11,12,30,37–41] have however shown that high initial machine costs of L-PBF are justified and have a reasonable payback period. The profits depend on how efficiently machines are utilized over their economic lifespan, the up-time of L-PBF equipment must remain high. Identifying bottlenecks and increasing the yearly output of a machine can be approached with DfAM rules and a simulation software tool, to improve the productivity.

Simulation tools can result in up to 75% productivity [9,29]. With the use of a simulation software, such as nTopology, Fusion 360, e-Stage, and 3DXpert for part optimization during the design phase, possible drawbacks may be identified and managed accordingly before actual production of part. Early detection of potential production bottlenecks aids in the selection of appropriate process parameters. These decrease in time spent on physical printing, scrap rate, and to achieve intended functionality. Following the proposed approach leads to a shorter product development period and enhances part performance [6,8,42]. For instance, redesigning of existing models that are intended for conventional methods involving subtractive machining is the main gateway for unlocking the full potential of L-PBF [43]. Benefits such as lighter weight, reduced lead time, energy, and higher cost efficiency may only be realized through design optimization with simulation driven DfAM of the parts [10,11,30,32,44]. Newest L-PBF machines have the capacity of simultaneous processing with multiple high-power lasers and high-speed scanners enabling increased throughput by saving energy, improved raw material utilization, and time use. The new L-PBF are also equipped with on-line monitoring systems to follow the manufacturing during build of part. Full utilization of the building platform work area is another straightforward way for increasing productivity. The use of skilled personnel enables little-to-no trial and errors, decreasing about 13% in part cost due to human error [29].

Currently, international bodies such as ISO and ASTM are developing the standards and validation methods for metal AM processes. Efforts to improve production volume and part size are ongoing.

1.3. Aim and Purpose of This Study

This study considers the impact of simulation driven DfAM on the LCC of L-PBF manufactured products. The motivation of this study is to provide a deeper understanding of the costs structure of metal L-PBF products and offer recommendations to support the decision-making towards the acceptance of the process. The potential of PBF has been broadly discussed in the studies [11,12,20,30,35,37,38] with the main focus on design and build phases, while the analysis of associated costs has been rarely considered, with attention paid mainly to cost components of machine, materials, and production [16,27,29,45]. There is the need therefore for a systematic model to analyze the cost structure of products made with L-PBF from the idea to end of lifespan. Understanding the cost structure will highlight the associated fixed and variable cost of L-PBF and help assess the impacts of its adoption. The cost structure in L-PBF is composed of the acquisition costs to get the system up and running and the operational costs to keep the system effectively working. This paper is based on a literature survey and focuses on the phases of LCC that characterize products. Understanding the fixed and variable cost of L-PBF allows for efficient choices to be made, for example, through exploiting the full utilization rate of machines. Phases of LCC included in this study are design, manufacturing, use (operation), and end of life (EOL). This study intends to provide the background information of possible costs, design choices, and highlight the means to reduce overall cost. The key cost elements of the different phases are identified with an explanation of their effect to remove the complexities from the decision-making process concerning the application of L-PBF.

This study was executed at LUT University with help of project Metal 3D Innovations (Me3DI) funded by the European Regional Development Fund (grant number, A74131), and project Manufacturing 4.0 (MFG4.0) funded by the Strategic Research Council at the Academy of Finland (grant number, 335992). The Me3DI project (duration 1.9.2018-31.12.2020) aims to establish a knowhow cluster of metal AM to South Karelia (Finland) and is executed by industrial partners and research groups of Steel Structures and Laser Materials Processing and Additive Manufacturing of LUT University. The MFG4.0 project (duration 1.1.2018 to 31.12.2023) aims to investigate how digital manufacturing will change fabrication in Finland and is carried out by the University of Turku, University of Jyväskylä, University of Helsinki, and LUT University.

1.4. Expected Results

This study will highlight the industrial benefits of L-PBF to improve efficiency and cost-effectiveness. As companies continue to adopt to L-PBF, presented case studies will offer exemplary application and assist in making effective and feasible choices for metal based products. The integrated simulation driven DfAM/LCC model will aid in the recognition of an appropriate decision rule for economic evaluations in decision-making. This study will also serve as a guide for analyzing whether investing in the L-PBF process is worthwhile or not to the business portfolio.

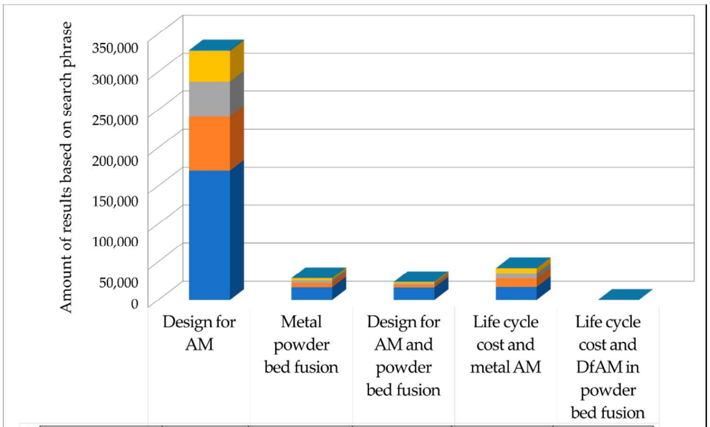
2. Materials and Methods

A search in the Web of Science database was conducted within the scope of this review. The phrases used to track the appropriate literature include:

- Design for additive manufacturing.
- Life cycle cost in powder bed fusion.
- Life cycle cost metal additive manufacturing.
- Design for additive manufacturing in powder bed fusion.

- Life cycle cost and DfAM in powder bed fusion.

The review data were obtained from four databases, Google Scholar, SpringerLink, Science Direct, ProQuest, and IEEE to validate results. These web bases were chosen as they cover wide and diverse reviews for specific research studies. The review was limited to 15 years (2005–2020) in agreement with the evolution era of AM. LCC studies include definitions outside of this time frame. Figure 2 depicts the outcome of web search with key phrases.



	Design for AM	Metal powder bed fusion	Design for AM and powder bed fusion	Life cycle cost and metal AM	Life cycle cost and DfAM in powder bed fusion
IEEE Xplore	939	16	0	2	0
SpringerLink	40,455	2887	1711	6974	11
ProQuest	45,959	3131	1,798	6110	16
Science Direct	71,040	5845	3620	11,448	20
Google Scholar	170,000	16,600	16,300	16,900	120

Figure 2. Representation of the web data base and number of literature hits between 2005–2020 related to this review.

Figure 2 shows that there are gaps in the level of studies relating to LCC and L-PBF. One may argue that the earlier terminologies of this methods could be the reason. Never the less the difference in literature is vast.

2.1. *Simulation Driven DfAM in L-PBF*

Design for manufacturing and assembly (DFMA) is a conventional systematic method to design and optimize parts, which is produced with traditional methods, such as CNC machining and casting, which aims to increase the manufacturability, quality, performance of products, and to reduce time and cost [18,45–47]. DFMA considers traditionally design goals and the constraints set by the applied manufacturing methods to ease manufacturing and assembly.

AM methods differ a lot from the conventional manufacturing processes as the constraints set by tooling and fixtures in conventional processes are non-existing with AM. However, there are specified guidelines and rules to the application of each of the AM methods for effective and successful use in industrial applications. Conventional DFMA can be described as the practice of designing and optimizing a product together with its production system to reduce development time and cost, and increase performance, quality, and profitability [46]. simulation driven DfAM rules substitute the methodological guidelines of DFMA in conventional manufacturing as these production technologies vary in principal level from each others [46–48].

Mechanical properties and microstructure of metallic L-PBF parts depend on process parameters (e.g., scan strategies, spot size, layer thickness, amount of energy used, etc.), raw material properties, part geometry, support structures, and environmental factors [2,18,29,49–51]. Process optimization approaches are applied to assess the impact of above-mentioned factors on the attainability of desired objectives such as functionality, aesthetics, and efficiency [16,42]. Several studies have highlighted the benefits of using simulation driven DfAM to achieve desired requirements and function [6–8,18,42,52–55]. The scan strategy refers to the type of scan pattern, the number of scan count, and the orientation of scanning paths in respect to each other in specific areas within the single layer. The scan strategy has the potential to impact characteristics such as porosity, microstructure, and formation of support structures and surface roughness of built parts. The selection of processing parameters such as the scan strategy must be done to avoid any defects that might result in undesirable features [2,20,49,56–58]. For instance, warping as a common defect in L-PBF [20] is minimized when the randomized scanning pattern is applied, as it prevents the buildup of residual stresses during processing. Another way to avoid warping is by providing sufficient adhesion surface contact between the part and build platform [19]. Rotating the scan pattern is a third way to alter the stress anisotropy resulting from the area localized power distribution within a single deposited layer [49,59].

Studies have shown that material properties can be tailored to achieve process optimization [49,56]. The localized variation of material stiffness can be used to achieve design goals. The material factors affecting the quality of print are: Phase, magnetic functional grading, and grain distribution as controlling parameters to achieve set goals of products. These findings are especially valuable in the context of multi-material AM products development [49,56].

The support structures for metal parts must fulfil the main functions of offering support for initial layers, prevent warping by the anchoring part to the building plate and conducting heat away from the part [19]. This improves the heat exchange capacity to avert reduction of mechanical properties. The use of support structures must be incorporated based on need. The support structures must be designed to have minimal need for material and ease of removal. For instance, initial simulation-based analysis of the support structures performance will reduce the numbers and complexity, being favorable for the physical separation of ready built parts from the base. The amount of work in removing the support structures after the building process can either be simple or complicated, depending whether the overhangs are present and their location on the finished part. Structural supports are mandatory in designs with overhangs regardless of increasing the overall manufacturing complexity. The idea has been formulated to be more specific: "Locating the scan pattern is a third way to alter the stress anisotropy resulting from area localized power distribution within single deposited layer" [49,59]. The chosen method reduces time usage and cost, thus, the designing of parts with the recommended 45° and even 10° overhang angle for self-support structures must be used to eliminate the need for structural supports. Commonly acceptable design rules are shown in Table 1. An exemplary application of these rules is applied to the design part in Figure 3.

Table 1. Design rules based on geometrical features suitable for metallic laser PBF (L-PBF). Adapted from [34,60].

Feature	DfAM Aspect	Recommended Minimium Dimension
1.Supports	The maximum angle a wall can be printed without requiring support	Always required
2.Supported walls	Connected to other structures on at least two sides	0.4 mm
3.Unsupported wall	Connected to the rest of the part on only one side	0.5 mm
4.Holes	The minimum diameter of hole printable	Ø 1.5 mm
5.Pin diameter	The minimum diameter of a pin can be printed at	1 mm
6.Minimum features	The recommender minimum size of a feature to ensure it will not fail to print	0.6 mm
7.Wall thickness	The minimum wall thickness to ensure a successful print for most materials	0.4–0.5 mm
8.Escape holes	The minimum diameter of escape hole for removal of build material	3–5 mm
9.Gapsize	Acceptable gap widths	≥0.4 mm (dependent on laser spot)

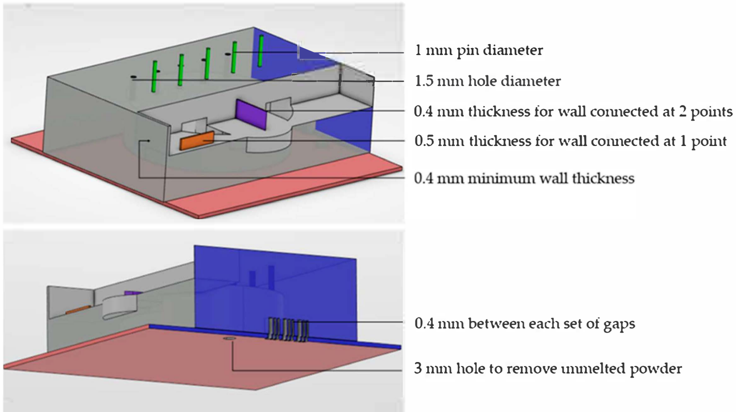


Figure 3. Example of applying DfAM geometrical recommendations in the part design.

The L-PBF process is heavily influenced by case-specific equipment and material, thus a general recommendation such as the given list in Table 1 and Figure 3 may not apply to every L-PBF system [34]. Existing DfAM rules concentrate on promotion or suppressing of a specific geometric shape such as minimum and maximum values of size, inclination angle, allowable bridging distance, etc. [60]. The application of DfAM rules offers an effective and efficient method to design suitable parts for L-PBF manufacturing.

2.2. LCC in Industrial Manufacturing

LCC is comprising associated costs of any process, product, or service in a period between idea generation to the end of life of the part [29]. With LCC, a company is able to carry out an economic evaluation to assess the feasibility of the upcoming project. Part design in ways that consumption of resources and cost-effectiveness of production are accounted for forms a basis for decisions. For instance, reducing the weight of the component is usually one of the main targets that influences the guidelines of design, thereby affecting the decision whether L-PBF is suitable for a specific manufacturing task. The outcome of these evaluations can help companies make decisions to achieve cost-effectiveness utilizing L-PBF [49].

LCC is defined as "the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission" [61]. LCC is also described as "cradle to grave costs summarized as an economics model of evaluating alternatives for equipment and projects" [62]. The life cycle of any system is characterized by cash flow, sales, and profit. Any company aims to identify the possible loopholes in operations and targets them to reduce future risks. The inclusion of operational and EOL associated costs during the designing phase in an LCC analysis will help identify ways of averting future compliance fees or fines. Operational and EOL costs are incurred within the use phase and EOL phase, respectively. It is possible to manufacture lightweight components with L-PBF, thereby reducing fuel consumption while the part is in service. As a result, less emissions are produced when the original design is replaced with lightweight components consequently reducing the fuel consumption in the use phase [29]. Companies are able to save on purchasing environmental quotas and emission certificates as less CO_2 is being produced.

2.3. Benefits of LCC Analysis for L-PBF

The design of the product and its performance and life cycle must be carefully planned out already in the beginning of the project [63]. A comprehensive assessment of the various work stages allows maximizing of profitability. The costs structure can be managed within a specific phase and to the entire life cycle [29,49,64]. The inclusion of all associated costs to the LCC helps reduce the single unit price and achieve a fair target cost. The target cost is the final cost of a product or service to achieve to generate the desired level of sales revenue and profit [65]. The designing phase must consider functional and environmental factors. This can lower some future costs such as, operating, maintenance repairs, and environmental clean-up costs at the EOL phase. Different models have been proposed to study LCC [29,46,64,66]. The classification of LCC phases in this study follows the idea of four main phases [64], as shown in Table 2. The costs associated with metal powder acquisition is excluded from this review.

Table 2. Representation of life cycle cost (LCC) phases of L-PBF manufacturing.

Phases	Type of Cost
1. Design [1]	research, development, design
2. Manufacturing (Build)	machines, material, labor, post-processing overheads, depreciation, test and validate
3. Operation (Use)	fuel cost, warrant claims, maintenance, CO_2 charges/fines
4. EOL	environmental clean-up, reuse, remanufacture, recycling, disposal, and decommissioning

[1] Adapted from Lindemann et al. and Garrett [29,64].

Cost structure in L-PBF is formed on the expenses of equipment acquisition, functionality maintenance, and depreciation costs [46]. The estimation of cost efficiency was performed in study of [46] based on an analysis of the utilization rate of the build platform. This study compared the direct production cost of printing single and multiple parts using L-PBF. The cost of part manufacturing was including energy, raw material, and machine costs. The machine cost structure comprised of purchase cost of machines, its maintenance, and expenses of consumables such as shielding gas. A simultaneous build of similar or dissimilar parts to the fill platform was able to reduce time and cost. It was concluded that energy consumption can be reduced by nearly 81% and production costs by 6% when the platform is utilized at full capacity. It was demonstrated that costs of L-PBF can be optimized, however, the work was limited only to phases of design and manufacturing. For assessing the economic benefits of L-PBF production, entirely, other stages of the product life cycle must be accounted for, including the evaluation of cost-efficacy of EOL.

The cost optimization based on process, material, and design structure for metal based AM has also been studied [16]. The review done in study [16] focused on the crucial aspects (part design and process parameters) concerning controlling the build time and cost. The benefits with the proposed methodology produced a 21% improvement in build time and a 15% reduction of total estimated production cost compared to addressing these themes separately. Processing factors such as beam velocity, laser power, and part optimization effectively influenced energy, material, and time usage. The result of the study showed the importance of integrating process design with topology design to economic efficacy in AM. A summary of the process variables, material properties, and structural design were defined based on the design compliance for cost minimization as Figure 4 shows [16].

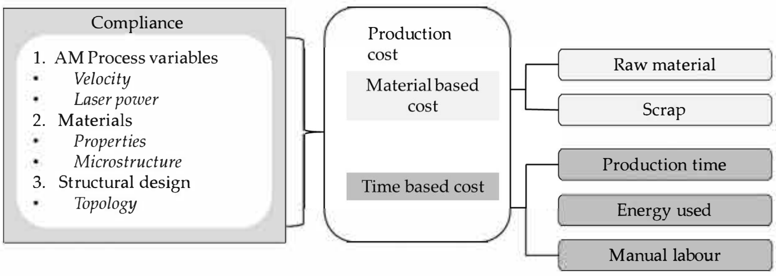


Figure 4. Schematic of concurrent method to reduce cost in metal additive manufacturing (MAM). Adapted from [16].

The Figure 4 shows the a further categorizing of the production cost of the study [16] into material based (raw materials, material lost during recovering, and recycling) or time-based (production time, energy, and labor)

There are six phases of the product life cycle according to the German standard DIN 60300-3-3 "Dependability management Part 3-3: Application guide Life cycle costing". The model developed accounts for intrinsic LCC of a product in which cost incurred by both manufacturers and consumers are considered from idea generation to the end of service life. This method is capable to identify cost drivers characterized by each phase. The study [29] has served as a basis for numerous works on the LCC analysis. The proposed method is expanded by assigning the impact factors to each phase and accounts their influence on controlling time and cost of the whole cycle. Figure 5 presents a summary of the LCC model discussed in detail in [29].

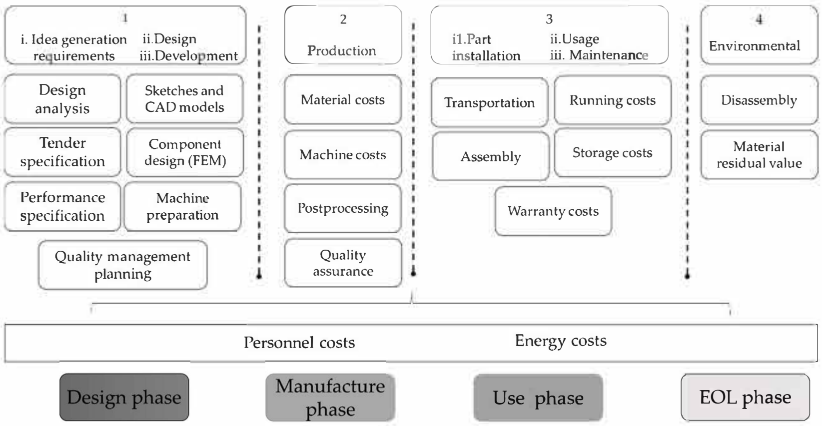


Figure 5. Schematic of the LCC model in the study of Lindemann et al. (2013). Adapted from [29].

The LCC model shown in Figure 5 includes four main cost areas:

- Initial development and design cost.
- Manufacturing costs, such as energy, material, etc.
- Operating costs, such as energy, waste, maintenance, etc.
- Environmental costs and benefits, such as emissions and residual material.

2.4. Case Studies

The benefits of energy efficiency, improved productivity, and functionality provided by L-PBF to automotive, aerospace, and other applications are explored in studies [20,23,24,26,44,67–71]. These studies highlight the benefits of designing web-like, lattice, conformal flow channels into parts for improving productivity, functionality, aesthetic, etc. aspects and reduced manufacturing steps and time. In studies [20,44,70,71], the benefits of complex internal flow channels, lightweight, net-like structures, function, and part consolidations using various L-PBF methods are presented. The results of such designs are improved stiffness, material efficiency, appearance, and better cost efficiency throughout the life cycle of products [20,60,72]. Figures 6–8 show the example cases of using L-PBF to make efficient (lighter, stronger, less assembly required), complex, and customized metal parts with improved functionality and aesthetics.

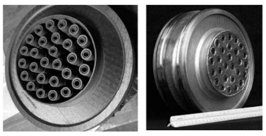
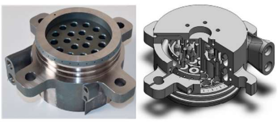
Products	Part count of traditional and AM methods	Additional benefits
(a)  28-element Inconel® 625 fuel injector by NASA	Reduced part count from 163 parts to 2 parts	• Lighter weight • Approximately 70 % saving in total cost
(b)  3D-printed coaxial injector for rocket engine by German Aerospace Centre and 3D Systems	Number of part counts reduced to single part from 30 parts	• A 10 % weight reduction • Cheaper production cost with PBF

Figure 6. Example of metal aerospace designed liquid fuel injectors (**a**) by NASA, reproduced from [20,70] and (**b**) three-dimensional (3D) systems reproduced from [70] with permission from 3D systems.

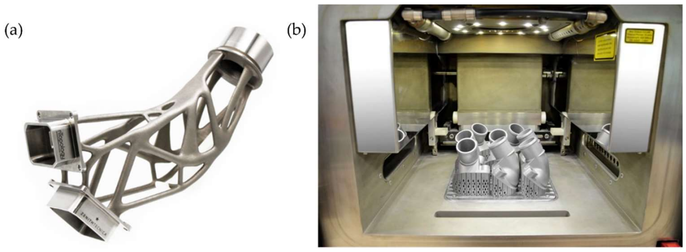


Figure 7. Representation of optimized (**a**) titanium spacecraft bracket, reproduced from [44] with permission from nTolology and (**b**) aluminum/silicon printed thermostat covers attached to the build platform. Reproduced from [71] with permission from Daimler AG.

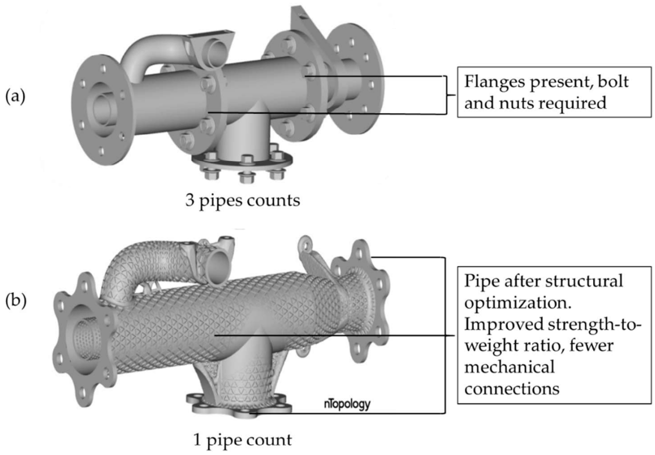


Figure 8. Case studies including. (**a**) classical assembly of pipes and (**b**) redesigned pipe assembly as consolidated a pipe assembly with conformal ribbing. Reproduced from [44] with permission from nTolology.

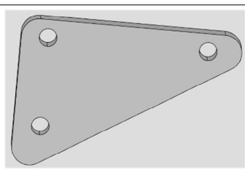
The optimization solutions presented in Figures 6–8 show the usability of L-PBF to lessen the number of parts needed, improve performance and aesthetics without compromising functionality, durability, and service life. Examples presented in Figures 6 and 8 show how L-PBF is useful for integrating multiple parts, thereby reducing the part count. The case shown in Figure 6a resulted in a shorter manufacturing time and fewer steps, part count decreased while its performance was improved by fluid flow optimization. The detail shown in Figure 6b received improvement in a conformal flow channels design. Number of parts (structures shown in Figure 6a,b had 163 and 30 parts) was reduced after redesign to two and one. Manufacturing steps, time, and costs were also reduced. The total time of manufacturing the part shown in Figure 6a was only four months, which is almost one-third (1/3) less than the needed time with traditional methods. The production cost was reduced by 70%, while performance properties were enhanced. Figure 7a illustrates how part optimization may be exploited to improve stiffness in aerospace and automotive applications for making effective and efficient lightweight components. High strength and temperature resistance thermostat covers were economically produced with L-PBF methods for old truck models. Figure 7b presents an example of making spare parts to replace old generation models with a reliably high original equipment manufacturer (OEM) quality. Conformal ribbing is one of the ways to reduce component weight, however this is not possible with classical methods. As shown in Figure 8, existing parts can be redesigned for applying advantages of AM and simultaneously preserving functionality. Novel design reduces the part count and manufacturing steps and time needed for design optimization. Removal of the two mid flanges demonstrates superiority over traditional manufacturing methods, where the part design is typically intended to suit specified manufacturing and assembly rules [44]. In addition to fewer production steps, tools, materials, and shorter manufacturing time provided by L-PBF, functional properties can be preserved or enhanced, and costs minimized.

Resources in L-PBF must be managed to reduce waste and inefficiencies to foster the shift from linear to circular economy. An example of how the Materialise Magics (Materialise, Technologielaan Leuven, Belgium) can help achieve such objectives with attention to reduction of time, raw material usage, scrap, and overall cost in metal AM methods, is shown in Figure 9.

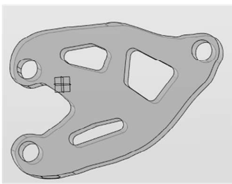
(a) Example case of simulation-driven DfAM metal part

Data preparation time	5 hours	< 0.5 hours
Average build time	30 hours	
Machine set up	3 hours	
Post processing	4 hours	< 2 hour
Number of build per year	186 (70 % utilization rate)	
Average material consumption	1.2 kg	
Build chamber	1 × (250 × 250 mm)	
Material	Titanium	
Software	Materialise Magics, (SG+ module)	
Re-build ratio	15 %	< 0
Operational cost / build without simulation: **$ 2,633**		
Operational cost / build with simulation: **$ 2,500**		

(b) Example case of simulation-driven DfAM design



without simulation driven design



Simulation driven design: optimised design

Figure 9. Example of (**a**) production cost reduction and (**b**) optimized design using a simulation-driven preventive method. Data in (**a**) from [9].

The base of building chamber for the case shown in Figure 9a was 250 × 250 mm. With the appropriate software and qualified personnel, only 10% of the time usually spent in the design stage was used, which translates to savings in cost. Use of simulation software prevents about 75% of defects and failures through virtual simulation before actual production. For instance, time saving of 2 h per build during post-processing adds up to 372 h annually. The number of hours saved in data preparation would equal to 837 h, assuming that each build has a different product design. The 15% re-build ratio, which is a measure of how often the build is repeated during production due to design failures, can be eliminated with the use of simulation. This halves the scrap rate during the manufacturing phase, totalling up to 50% of overall production cost. One example of the detail shown in Figure 9a, is that the efficient design of the parts takes only one-tenth (1/10th) of typically used time and doubles the speed of manufacturing of build phases. One more outcome is a 20% reduction in material consumption depending on defined parameters of each specific case. Figure 9b shows an optimised CAD model. The optimization goal was to improve stiffness by 30% with 40% mass reduction. These goals were effectively achieved using the part design and generative functional design apps of Dassault Systèmes 3dexperience (Dassault Systèmes, Vélizy-Villacoublay, France). The functions and requirements of the design were either preserved or enhanced.

2.5. Integration of Simulation Driven DfAM and LCC of L-PBF

Productivity can be described as a measure of how well input resources are turned into profitable useful outputs in a specified time. Resources include but are not limited to machines, labor, raw materials, investments, energy, etc. [33]. L-PBF offers several means to control outputs with optimized designs which influence materials, energy, time usage, and whole costs. With L-PBF, costs of production may also be altered with the simultaneous building of similar or dissimilar parts from the same material [35,45]. The versatility of L-PBF has potential to increase the efficiency of energy and material usage. Flexibility provided by L-PBF in design stage should reasonably be applied to avoid overcomplicating the model. This will ensure that components fulfill demands set to complexity, weight, functionality, and aesthetics while reducing the manufacturing time and cost.

The possibility to modify the part design for a functional requirement is the main benchmark in L-PBF [11,16]. A model of LCC generated in this study is shown in Figure 10. The LCC model is based on five assumptions:

- The designed part is applicable in a multiple function.
- Parts are made with stainless powder.
- Metal powder is sieved and recycled to be re-used in production.
- Parts are reusable after the initial usage.
- At EOL, parts are considered for repairs prior to being recycled.

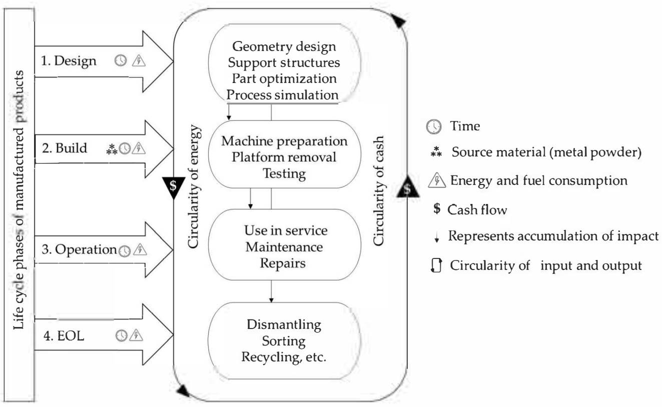


Figure 10. Representation of the LCC model for products made with L-PBF showing interrelations between phases based on time, energy, metal powder, and cash flow.

As it can be seen from Figure 10, design and manufacturing phases are interrelated to the remaining phases of the product life cycle. The literature review established that controlling parameters during the lifespan of components are largely dependent on time, energy, and raw material consumption. These parameters can be controlled during the design phase as denoted by the symbols in Figure 10. The utilisation of simulation software to design optimized components can reduce the rate of failure occurrences. While the physical controlling of material, time, and energy usage is realised during the manufacture phase, they are set already during the design phase. Creating optimised designs and proper support structures can prevent build failures such as distortion and lack of fusion voids. As it can be observed from Figure 10, the consumption of fuel and energy can be controlled during the use phase. The possibility to make effective or efficient design suitable for a specific application can reduce the consumption of these utilities. Lifetime of components is also increased when optimized parts are made. This corresponds to the increased service time for components. The use of L-PBF reduces also downtime in the operational phase with an on-demand and on-time manufacturing option. During EOL, time and energy usage can be reduced if the designing phase was planned to consider the ease of disassembly and related EOL actions. The circularity connecting the different phases denotes that cash continues to flow within the whole system. The design phase allocates for approximately 20% of overall product cost, while around 75% of the manufacturing costs are fixed (e.g., cost of equipment and raw materials). The observed change is obvious when compared to the last decade, when the design cost was making up only 5% of the overall product cost [13].

The simulation driven DfAM in L-PBF primarily can be applied in the activities carried out during the design and build phases, as shown in Figure 11. Actions of these phases need to be optimized to achieve cost efficiency of the entire life span of metallic built components.

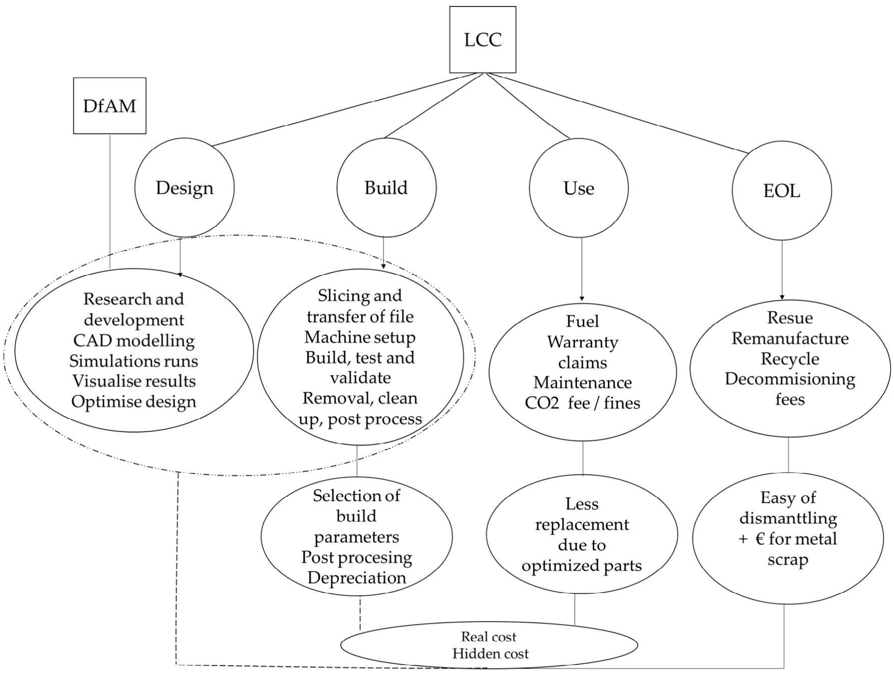


Figure 11. Schematic of activity-based cost structure breakdown for L-PBF of metallic components.

The dotted lines in Figure 11 denote some of the characteristic activities which can be targeted to get the needed cost-effectiveness in L-PBF. The designing of parts should be planned to manufacture efficient products and to eliminate defects. The designing and building of optimized and effective structural designs [9,18,39,73] based on a computer driven-design must be preferred to avoid undesirable operational costs. The selection of building parameters must also correlate to cost-effectiveness. The dismantling and sorting of residual material must be considered during the part designing stages as it can directly affect the time and personnel cost after their useful life. Design engineers must understand the implications of part designs during the use and EOL phases in advance to be able to create models that comply with all the phases of life cycle of the products. LCC analysis must be applied to reduce the real and hidden cost. The real cost can be defined as a tangible expense to acquire physical machines and equipment to produce a good or service [74]. The hidden costs can be described as an intangible cost which are unavoidable to the successful running of a company. Examples of these include software tools, training, maintenance, supplies, and upgrades [75].

3. Results and Discussion

A summary of the review scope used in this study (shown in Figure 2) determined that the highest number of published articles are addressing the topic "design for additive manufacturing", followed by "LCC in metal additive manufacturing", "metal powder bed fusion", "design for powder bed fusion", and "Life cycle cost and simulation driven DfAM in powder bed fusion". Several of the results were only vaguely related to L-PBF, rather discussing AM methods in general. Concerning LCC, it becomes evident that the topic has gained measurable attention in the manufacturing sector, nevertheless the number of publications addressing metal AM is limited. Several studies considered LCC as part of sustainability or life cycle assessment studies. The majority of the literature involves non-metal materials and AM methods in general. The web search of LCC in PBF or L-PBF costs gave only 167 results from all three databases used, without any findings on the IEEEXplore platform.

The current trend in the state of the art of L-PBF is the prediction of part performance through design improvements and process simulation. The development of L-PBF machines has led to higher production capacity. Simultaneous processing with multiple high power lasers in the work area, high-speed scanners, and an adjustable layer thickness increase the throughput [41,68,76,77]. Use of the simulation driven DfAM software adds value to creation, optimization, and simulation analysis of designs before actual manufacturing. Technical and software advances applied simultaneously minimize defects, labor, material usage, scrap rate, and time needed for production. Support structures and their design form a section of optimization studies and influence the cost of L-PBF. Support structures are currently a highly significant topic for exploratory research.

The cost efficiency and productivity play an important role in the acceptance of L-PBF. The current study highlights the need for costs related studies, as lack of information is hindering adaptation of L-PBF. The initial machine and metal powder costs have been identified as a main deter to its acceptance. Studies on cost-effectiveness in L-PBF are necessary to promote and increase knowledge about the cost benefits that L-PBF presents. In addition to design freedom, the LCC model for L-PBF provides designers, manufacturers, and end-users alike a new market opportunity in metal L-PBF.

The weight cost of raw materials (e.g., powders, filaments, etc.) of AM is up to eight times more than the materials used in conventional methods (e.g., ingots, granulates, etc.). Use of the L-PBF is however justified, as the process facilitates part consolidation [78], lightweight products [20], and has an effective material utilization rate up to 99% [79]. The initial fixed cost of L-PBF system is earned back by a low amount of stand-by time and possibility to produce unique designs. Part consolidation, resulting gains in functionality, and planning out EOL activities decreases expenses as well. Cost-cutting is possible in all of the product life phases through modifications in design, virtual simulation of manufacturing prior to physical printing, and planning the actions for EOL. Monetary savings have so far been most evident in automotive and aerospace sectors, where the weight of re-designed part was reduced by 40% and 70%, respectively resulting in reduced fuel consumption and lower environmental taxes during the exploitation [21,29,80].

The L-PBF process would benefit from studies involving simulation driven DfAM and LCC to highlight the production bottlenecks and methods for controlling the cost in industrial applications.

Well informed decision-making in industrial L-PBF outweighs the high price of initial investment by controlling the running costs. Compliance with environmental legislations becomes easier by making sustainable decisions, in addition, possible fines during the use and EOL phases can be avoided. Cost generating issues can be avoided with initial consideration of functional requirements already in the design phase. An assessment of L-PBF with a life cycle engineering quantifies advantages obtainable in energy consumption, maintenance, and environmental impact. The transportation carbon footprint is less with localized manufacturing and reduced logistics needs. A shorter production chain gives companies a competitional advantage by faster delivery times. Unlike traditional manufacturing processes, L-PBF is a highly flexible process allowing swift modifications in design, prior or during production.

4. Conclusions

The aim and purpose of this study is to provide a deeper understanding of life cycle costing (LCC) accumulation in metal part production with laser based powder bed fusion (L-PBF) which is one of most widely used additive manufacturing (AM) technology for metal production. The paper outlines the factors involved in decision-making in choosing the manufacturing method. The geometrical design of the part has a large influence on the overall cost of the product. The LCC analysis of L-PBF equips companies with means needed for developing process models for tracking costs based on the analysis of acquired data. part optimization with simulation driven design for additive manufacturing (simulation driven DfAM) and simulation tools simplifies the choice of processing parameters and results in enhanced functionality and efficiency. AM is known for its design freedom, L-PBF has attracted interest from the industry as the technique allowing the design and manufacture of customized and complex metal products. Current optimized designs suitable for metal L-PBF improve material and energy efficiency utilizing existing L-PBF systems. The inherent problems such as porosity, inhomogeneous microstructure, and deficient surface quality are rapidly improving as a result of applying DfAM rules and IT simulation tools.

The industrial relevance of this article is to provide information for decision-makers to control costs by integrating the design rules with consideration of whole life cycle of the product, not solely on investment costs. This paper aims to contribute to the understanding of cost structure by a holistic evaluation of costs within specific life cycle phases. The main conclusions of simulation driven DfAM and LCC to L-PBF are:

- Effective application of simulation driven DfAM is an efficient approach to improve design and analysis components for L-PBF.
- Application of simulation driven DfAM in L-PBF for optimized and energy-efficient designs usually results in an enhanced part functionality and cost-effectiveness.
- With on-demand and on-time manufacturing, L-PBF reduces operational and inventory costs of companies and gives them competitional advantage.
- LCC aids in the quantification of costs involved and evaluation of impact of energy, material, infrastructure, personnel, and machine productivity related expenses.

The proposed LCC models shown in Figures 10 and 11 aim to be applicable for testing the effectiveness of L-PBF in an industrial setting. Findings presented in this study offer a holistic method to the LCC analysis in metal L-PBF. For improving the statistical significance, more research on the practical application of simulation driven DfAM to metal L-PBF is needed.

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Publication V

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Prospects of laser based powder bed fusion for metal electrodes: A review

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Prospects for laser based powder bed fusion in the manufacturing of metal electrodes: A review

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A B S T R A C T

Additive manufacturing, (AM), includes seven subcategories that can directly manufacture components structures from a computer-designed model layer by layer. Laser-based powder bed fusion (L-PBF) is one of type of the subcategories of AM. L-PBF is a fast and cost-efficient production method that offers the advantages of being implementable with a diverse range of raw materials, possessing a high level of freedom in customization, and producing less waste. L-PBF can potentially enable the production of hierarchically complex shaped electrochemical separation units. This study examines the use of L-PBF for the fabrication of metal electrodes for electrochemical processes. The aim is to address a literature gap by presenting a state-of-the-art review of L-PBF electrodes used in electrochemical cells. The study investigates existing research on electrochemistry and identifies potential benefits from use of L-PBF metal electrodes. Electrochemical reactors in industry require electrodes with a large electrode/electrolyte interface that can hold electrolytes efficiently and reduce the diffusion path of electrons and ions on the active surface of electrode. Meeting these demands require electrodes with specific characteristics such as high surface area and improved mass transport. This review shows that L-PBF can manufacture optimized electrodes satisfying the requirements for electrochemical cells in industrial applications

1. Introduction

Additive manufacturing (AM), popularly known as 3D printing, is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [1]. The 3D model refers to computer-aided design (CAD) models, which are either designed from sketches or generated from scans of exiting objects. Scanning of component geometry to a CAD model is often used in reverse engineering, where 3D laser scanners can be used to obtain outer geometries. Inner features of the product are, however, not detected by this method [2–4].

AM methods are divided into seven subcategories, according to ISO/ASTM 52900-2015 [1]. In its category, powder bed fusion (PBF) is defined as a "*process in which thermal energy selectively fuses regions of a powder bed*" [1]. Thus, powder bed fusion refers to AM systems with a building area where raw materials in powder form are laid for melting [1,5]. PBF is further grouped into two subcategories according to the energy source, namely, laser-based powder bed fusion (L-PBF) and electron beam-based powder bed fusion (E-PBF) [6]. The two PBF methods differ in terms of the parts, type of heat source, resolution, process layout, need for a vacuum in the chamber, and melting mechanism of the powder.

Recent studies have indicated that the emerging metal AM method of L-PBF is gaining acceptance in biomaterial engineering and industrial engineering. L-PBF finds usage in the electronics, automobile, aerospace, and petrochemical industries [7–15]. Furthermore, L-PBF manufacturing has attracted attention in the last decade in research institutes and industrial companies as a frontier to the digital revolution, termed Industry 4.0 [7–13]. The technique is predicted to become a viable option to conventional manufacturing in cases where lightweight, complexity, and cus-

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tomization are beneficial [16–18]. L-PBF offers new opportunities to multi material macro/micro metal components, potential option to cost-effective, complex component and customization production [19,20]. Medical field is one sector using L-PBF and multi material to create unprecedented designs to meet specific needs of patients [21]. The integration of L-PBF and new range of functional materials is a viable means to create high value components which require lightweight and customized designs to leverage cost [22,23]. New emerging functional material offer new ways of hybrid manufacturing of multi-material [24], multi-body design [25] and or multi-manufacturing method [26,27] to overcome some of the existing limitations in manufacturing systems. For example, multi-materials and consolidated designs can improve performance by creating components of improved homogeneity with seamless joints and characteristics. This reduce risk of joint leakage and thermal bridges in applications where joints may affect performance [28,29]. Electrodes are components whose optimal performance benefits from complex geometries and customization, making L-PBF a promising alternative for electrodes production [30,31]. In this article, electrodes made from metal materials and L-PBF are presented. The review highlights some of the benefits L-PBF, offer to electrochemical separation processes. L-PBF can build electrodes of varying structural composition, surface roughness, geometry, orientation, and electrocatalytic activity, [30,32]. Consequently, controlling and tuning electrode performance can suit different conditions and applications [30,31,33].

1.1. Laser-based powder bed fusion

The first steps for producing parts with L-PBF comprise of idea creation, definition of functions, requirements, and restrictions, and designing and planning the sketches (or scanning) followed by CAD modeling of the desired products. In this initial phase, support structures are also added to the actual workpiece. The next step is converting the CAD model to a readable STL file format appropriate for specific construction machines where required. STL files describe only the triangulated surface geometry of 3D object without any color representation. In other words, STL conversion means the conversion of a solid digital model into a digital model triangulated surface model. Conversion to STL format is done in order to reduce the file size. The STL file is then sliced with special software to acquire the layer-by-layer readable G-codes data needed to print components on the machine system [34]. The L-PBF machine fabricates the physical components based on this sliced data. Machine set-up is done, together with slicing, following necessary modification, and selecting suitable process parameters before the actual building. The building of components follows layer by layer until the entire model is completed [35]. The powder is then removed, and the part is taken out of the building chamber with the building platform. The finished product is removed from the platform and supports before the part undergoes any required post-processing. **Fig. 1** shows the process steps and the equipment layout in L-PBF manufacturing.

1.2. Electrochemical processes

In electrochemical processes, oxidation–reduction reactions occur as charged ions either gain or lose electrons, which creates an electric current [37–39]. An electrode can act as an electron donor (cathode) or an electron acceptor (anode) [37]. In electrochemical contexts, an electrode can be defined as a half-cell between one or more ionic conductors and an electron conductor. Thus, electrodes are the combination of an electronically conducting material in contact with an ionically conducting phase. The half-cell consists

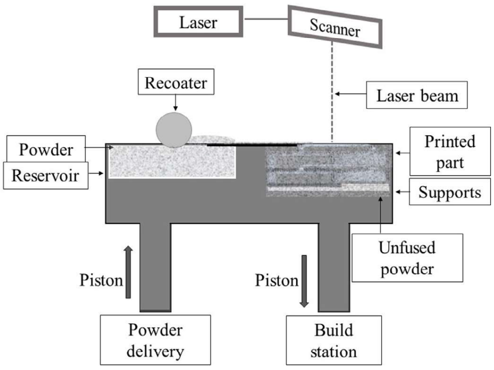

Fig. 1. Schematic of A) steps of L-PBF process, and B) layout of principle of L-PBF adapted from [36].

of at least one electron conductor and at least one ionic conductor (electrolyte) [40].

Material transport in electrochemical cells is achieved when fluid transfers electricity by flowing through a porous medium under the influence of a uniform magnetic field. The flow velocity, appropriate catalyst, and the high surface area of the electrode can increase the reactions at the surface of the electrodes. Recent advances in modeling and scaling two-phase solid particle/liquid electrolyte systems brought new research principles on chemical and electrochemical [41]. Additionally, researchers evaluated simultaneous mass transfer and chemical reactions. The combined effects of heat and mass transfer on Magnetohydrodynamics (MHD) flow of a water-based nanofluid form in a porous medium with the different forms of nanoparticles have been studied so far [42,43]. The unsteady flow of a fluid over a vertical plate embedded in a porous medium, with time-dependent velocity, temperature, and concentration, was considered at the different forms of spherical nanoparticles. According to the results, MHD and porosity parameters showed the same effect on surface friction than the velocity parameter. Through a drop in fluid velocity due to the porosity, the surface friction between the particles increases. The surface friction causes the force to prevent the relative motion between the electrolyte and electrode. This resistive force is due to molecular adhesion [42–44]. Based on the conclusions, as the fluid velocity decreases, the thermal boundary layer thickness and the concentration gradient close to the electrode decrease [45]. Besides, due to the drop in the fluid velocity and the concentration level, the chemical reaction parameter could be increased. In another word, as the chemical reaction parameter increases the fluid velocity as well as the concentration level decreases [46].

Combining porous L-PBF electrodes and flow reactors allows to create high-efficiency hybrid tubular cells with thin-film electrolytes for rapid generation of in situ oxidants for fast indirect electrosynthesis. Materials for electronic conductors include pure metals, metal oxides, carbon, and various alloys. Applications of electrodes include electrochemical machining (ECM), electrical discharge machining (EDM), detection of specific substances, water splitting, and rechargeable batteries (REBs) [13,32,47–51]. The steps of electrode manufacturing using L-PBF and areas of application are shown in **Fig. 2.**

The arrows in **Fig. 2** indicate directions of activity. The performance of electrodes can be improved by functional surface modification [37] as shown in **Fig. 2**.

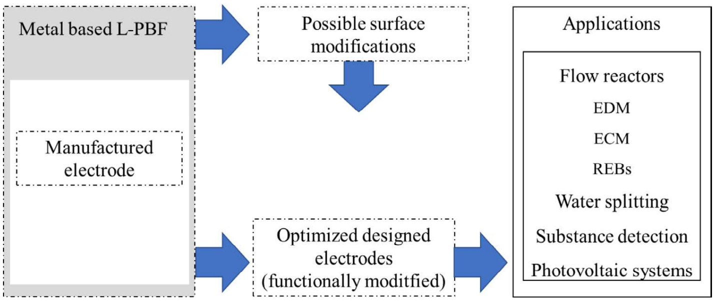

Fig. 2. Schematic of electrode manufacturing routes and application fields.

1.3. Aims of study

The use of AM in modern-day manufacturing offers design flexibility and material, energy, and cost efficiencies. The design flexibility offered by AM allows the design of complex and dimensionally accurate components to suit the specific needs of a diverse range of industrial applications [52,53]. Nevertheless, most existing studies have concentrated on AM to improve durability, performance, function, productivity, and esthetic aspects in industries such as the automotive, aerospace, and medical sectors [14,15,54–56]. There also seems to be a lack of published work looking at the specific issue of metal AM electrodes. This study partly addresses this research gap by reviewing research studies related to the AM of metal electrodes used in electrochemical processes. The work considers the potential benefits of using L-PBF in this field.

1.4. Methodology

This research is a comprehensive review of the state-of-the-art of AM/L-PBF for metal electrodes. The study uses the following scientific databases as sources for the literature reviewed: SCOPUS, Google Scholar, ACS Publications, Science Direct, and SpringerLink. The bibliographic search was conducted for the period 2005 to August 2020. The literature review used the following search terms:

1 Additive manufacturing * electrodes (include also studies done with the term “3D printing”)
2 “Powder bed fusion” AND electrodes IN electrochemistry (include also studies done with the term “3D printing”)
3 “Powder bed fusion” AND electrodes IN electrochemistry
4 “Laser powder bed fusion” AND “metal electrodes” IN “powder bed fusion”
5 Additive manufacturing * electrodes * electrochemistry
6 “Laser powder bed fusion” AND “metal electrode” AND electrochemistry

Fig. 3 shows the number of published articles related to AM and L-PBF for electrochemical electrodes classified according to Google Scholar, ACS Publications, Science Direct, and SpringerLink databases. The trend of yearly publication (only SCOPUS) is given in Fig. 4. The majority of the search results may be a combination of the same topics. For example, results for the search for “Powder bed fusion and electrodes in electrochemistry” were represented for different search term. found with the search for “Laser powder bed fusion and electrodes in electrochemistry”. Specific topics relating to metal-based electrodes with L-PBF were extracted from the search list to suit this study.

As **Fig. 4** shows, AM electrode studies have constantly grown since 2012, and specific studies on AM electrodes for electrochemistry began in 2015. The share of L-PBF of the review shows fewer studies on this topic relative to the total number of studies on AM for electrode applications from 2005 to the present. Many of the existing literature do not separate L-PBF for metal electrodes but rather has been treated as a part of generalized AM/electrode studies. Existing literature often categories such studies with the general term, AM; thus, the research result showing that AM for electrode manufacturing may include other L-PBF. The review includes studies published with “selective laser sintering,” a historical term for L-PBF. The authors assumed, based on random scanning, that many existing studies investigated plastic-based electrodes.

2. Design optimization of L-PBF for electrodes

L-PBF can be used to manufacture intricate and complex geometries from metal powder. The possibility of incorporating conformal flow channels within solid bodies, creating lattice frameworks and tortuous channels, and combining multiple parts into a single part can potentially enhance the performance and stability of electrodes [21,40,41]. This, permits several design optimizations in electrochemical applications [21,42,43].

The use of electrodes in flow reactions offers a practical approach to overcome mass transfer limitations employing higher surface area and confinement of the flow in micron or sub-micron sized pores [30,57]. However, flows through electrodes are opposed by inherent material electrical current resistance or boundary-imposed resistance due to layers and sizes [57]. Pressure-induced limitations in the flow channels can be counterbalanced with superposed basic flow induced by secondary flow patterns [57]. The mitigation can be achieved by increasing velocities using microfluidic devices or sectioning [57]. Microfluid devices diminish continuous boundary formation [57] through form-like media [58] and overcome any pressure-related flow resistance. The effects of flow rate on electrodes are discussed in [57–60].

2.1. Lattice and tortuous designs

The term lattice is interdisciplinary and can have different meanings in different disciplines and offer different benefits in different applications. Lattices can be incorporated into components for either functional reasons or as an esthetic feature. Some benefits of creating a lattice in components include better material usage efficiency, weight savings [8], greater surface area [61], and improved charge capacities [62]. A lattice truss in structural design is an arrangement of interconnected beams converging at a common point. The struts that form lattices are constructed through interlocking pins or rigid bonds. The conversion of solid metal bodies to mimic a form-like structure can tailor specific desired properties

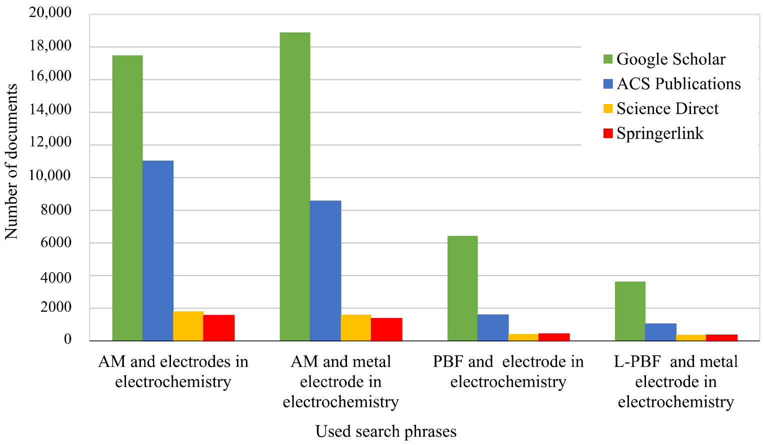

Fig. 3. Overview of literatures search results for AM for the databases Google Scholar, ACS Publications, Science Direct and SpringerLink.

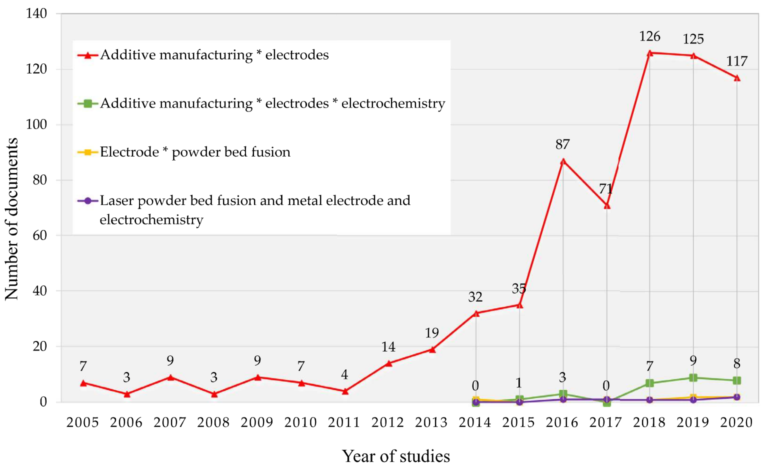

Fig. 4. Yearly publication volume of the considered search terms for the SCOPUS database.

such as stiffness, thermal conductivity, electrical resistivity, diffusion, and strength [63,64].

The use of design for additive manufacturing (DfAM) rules and simulation software such as functional generative design and COMSOL Multiphysics can automate the creating of effective and efficient lattices to suit specific flow configurations. The design of intricate structures in fluid flow components with such software is achieved using numerical simulations like finite element analysis (FEA) and computational fluid dynamics (CFD) [32,65]. CFD is a computer-based fluid mechanics tool that can be applied to evaluate fluid flow and related phenomena. FEA is a computer-based tool with which physical phenomena, often phenomena related to structural elements, can be analyzed using numerical methods [66]. Combining fluid flow, structural, and AM simulation can result in optimized lightweight components and better flow conditions [32,67], such as decreasing part weight and pressure drop. Using simulation-driven design allows the isolation and control of specific phenomena. It draws attention to possible ways to alter physical conditions [68] without impairing the performance and functionality of the component [69].

Unlike conventional manufacturing methods, L-PBF uses layer-wise deposition of materials, enabling sophisticated parts of complex shapes [64]. The possibility to manufacture components with little to no shape restrictions makes L-PBF an ideal technique for building components with lattice structures. However, L-PBF is inherently limited in part size and lot size. There is also the possibility of distortions and porosity, which can affect the building process or the reliability of the component. The lattice design needs to be planned such that there is a consideration of possible post-processing methods. The use of support structures for lattices offers more geometric freedom. Complex supports can however increase post-processing time and workload. Due to this rea-

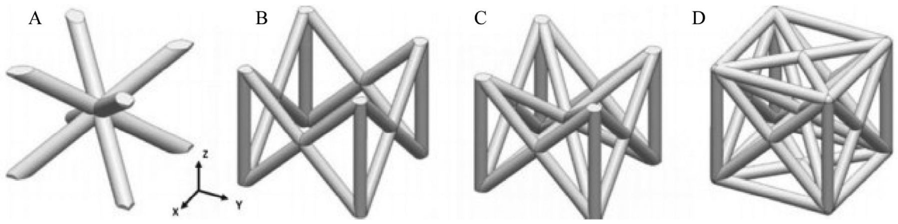

Fig. 5. Lattice structure and different configuration of unit cells: A) body centered cubic (BCC), Bb) face centered cubic with vertical struts (FCCZ), C) face and body centered cubic with vertical axis struts (FBCCZ), and D) face and body centered cubic with horizontal and vertical axis struts (FBCCXYZ) [70].

son, self-supporting designs are favoured over inherent overhang angles requiring structural support [70]. Complex geometries must be planned to correlate with the defined building parameters of the specified machine [70]. **Fig. 5** shows examples of configurations of lattice unit cells, arrays of struts, and connections.

As shown in **Fig. 5**, the unit cells of lattice structures can be a combination of different geometries. Each arrangement of cells in **Fig. 5** offers different properties to achieve a desired function. Lattices can be incorporated into metals, polymers, and ceramics of specified cells to define certain shape, size, and thickness [63,71]. L-PBF enables the creating of fully dense lattice-like metal components with tailored biological and mechanical properties [72–74]. Effective control of process parameters must be used to ensure optimal deposition to reduce the forming of undesirable pores. In electrochemical applications, the incorporating a lattice structure has a positive effect on mass transportation, electrical and thermal properties [62,71]. Additionally, the use of lattice-like structured electrodes creates an increased specific mass capacity compared to solid-blocked electrodes. The larger specific mass capacity increases interaction between the electrode and the electrolyte [75].

2.2. Fluid flow optimization

Flow in a liquid pipeline may be smooth or laminar flow. Flow turbulence can be altered through higher velocities or flow rates (Reynolds number). Reynolds number (*Re*) is “a *dimensionless number used to categorize the fluids systems in which the effect of viscosity is important in controlling the velocities or the flow pattern of a fluid*” [76]. Relative roughness is “*the amount of surface roughness that exists inside a pipe*” [77]. The roughness has no effect on laminar flow as liquids in laminar flow tend to move with a straight and smooth surface and thus are able to seal off any roughness [78]. The reverse is the case with chaotic flow as *Re* gets higher than 2100 [78]. The effect of roughness can be negligible as *Re* slightly exceeds the critical *Re*-number of 2300. For the reason that laminar sublayers can offset the effect of surface roughness. The transition from laminar to a chaotic state can occur over a range of *Re* [78–80]. Both laminar and turbulent flow can exit at *Re* between 2300 and 4000 [79].

Designing flow channels with segmentation [57] can help increase flow velocity. Creating segments impede the continuous growth depletion boundary which can help overcome the limitations of pressure-driven laminar channel flow by inducing secondary flow patterns[57]. L-PBF can be used to complex segmented features into for electrochemical separation unit with increased surface roughness, e.g., at flow boundaries, which often suffer losses due to flow viscosity. Theoretically, surface roughness decreases frictional and viscous losses in turbulent flows depending on the size and surface of the pipe used [80,81].Increased complexity of flow channel designs with controlled surface roughness and rounded flow joints are some of the benefits that can be obtained from using L-PBF to make metal parts for electrochemical applications. The incorporation of secondary flow into hydraulic applications helps optimize flow dynamics by creating chaotic flow in time and position. Designing flow channels with segmentation, zigzag patterns (see **Fig. 6**A) [82], and rounded flow joints (see **Fig. 6**C) [57, 28] are examples of means to achieve improved flow dynamics.

As can be seen from **Fig. 6**A), *Re* can alter the turbulence of fluid flow [57]. The simulation result in Fig. **Fig. 6**A shows only laminar flow at lower *Re* of 14. At larger *Re*, secondary flows are seen to be present, which intensify as the *Re* number increases. **Fig. 6**B and C show that the configuration of flow in a channel differs based on the sharpness or roundness of the respective inner corners. Traditional manufacturing methods and L-PBF can both manufacture rounded T-shaped pipe designs. The latter is preferred for such designs due to the flexibility and ease to make any shape without intensifying required labor. The flow configuration of metal hydraulic manifolds fabricated with an AM designed arc channel joint in **Fig. 6**C yielded improved efficiencies as follows [28]:

1 Smoother flow transition through a branch with an arc
2 Approximately 78% volume reduction from 535 cm3 to 116 cm3
3 Approximately 35% weight reduction 1.5 kg to 0.98 kg.

Three-dimensional (3D) electrodes including foams and felts can be used in electrochemical reactors to increase the active surface area of the electrode and the efficiency of the system. However, these irregularly shaped electrodes cause tortuosity and channeling effects and impose three to four orders higher pressure drops than would be generated with flat electrodes. AM/L-PBF can effectively manufacture turbulence promotor features with flow guiding structures. Optimizing electrodes with tortuous design can boost turbulence, which can increase velocity and enhance mass transfer without adverse effects on the pressure drop. In addition, L-PBF can be used to manufacture stainless steel electrodes with increased mass transfer coefficient of up to 76% [32] by incorporating complex tortuous flow channels. Tortuous configurations can potentially be used to control the performance of electrodes in, e.g., batteries applications [58]. **Fig. 7** shows three examples of complex-shaped electrode designs achievable with L-PBF, namely, Kenics, Ross low pressure drop (RLPD) and Sulzer mixer electrodes, respectively.

2.3. L-PBF and reverse engineering for optimized electrodes

Reverse engineering is an approach to learn from the architecture of an existing component and to use this knowledge to make new improved versions of the part. 3D scanning is one of the quickest ways to convert a physical part to a mesh-like digital format for editing and testing. 3D scanning, however, only gath-

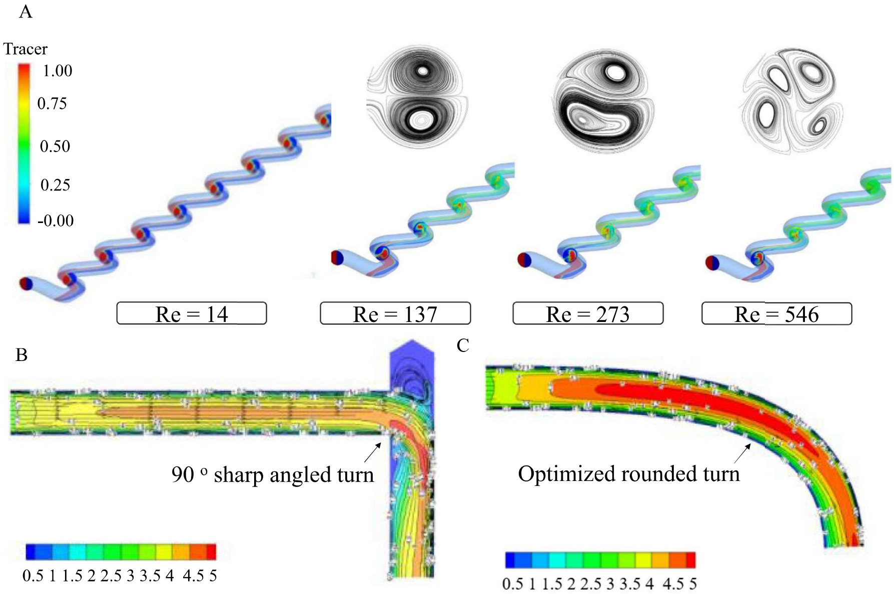

Fig. 6. A) Representation of simulated views of the effect of *Re* on zigzag joints channel design flow configuration [57]. An illustration of configuration flow with B) sharp joint and C) rounded joint inner corner designs [28] Fig. 6A) Reproduced with permission from Andre de V., InnoSyn. Fig. 6(B, C) Reproduced with permission from Yi Zhu, Zhejiang University.

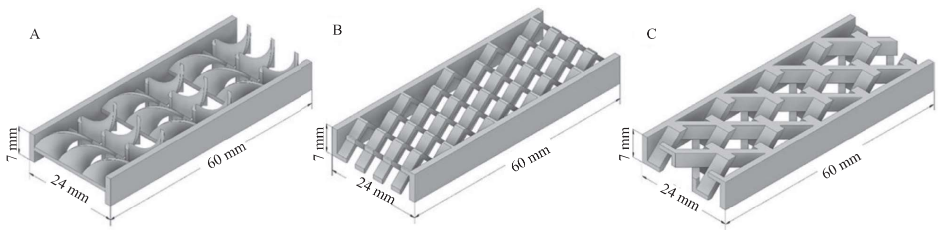

Fig. 7. Types of the structured 3D electrodes: (a) Kenics electrode, (b) RLPD electrode and (c) SMX electrode [58].

ers data about the outer surface of the product and does not provide information about complex internal structures. The scanning of complex parts via this contactless technology gives an overall shape and geometry via point cloud data [2,3] and in some simple cases helps to simplify the initial steps of designing and planning.

CAD software tools are used to convert these triangular models to a concise solid model for modification and testing. A robust and cost-effective reconstruction of a new model can be made on demand using rapid AM methods for a prototype or with L-PBF for a functional new part [2,3]. The use of reverse engineering and AM are potentially beneficial for simple designs of electrochemical engineering parts because re-engineering of existing components can easily and affordably be achieved without a need to create and plan new designs. **Fig. 8.** shows an example approach for the use of reverse engineering and AM/L-PBF for existing components (e.g., electrode).

As shown in **Fig. 8**, idea generation is carried out using the skeletal outer geometry of an existing component for new designs, thus reducing the lead time. Laser beam scanning is used to scan, collect, and filter high density cloud point data of the physical part without human interference. These cloud point data are then reconstructed using range images via reverse engineering and specialized software into solid 3D models or reconstructed surface data, as shown in the dotted region in **Fig. 8**. CAD software is a catalyst to this approach. These tools allow a virtual platform to imitate previous designs, detect and modify deficiencies, and simulate, test and perform quality control for redesigned tool parts. The building of the part follows after the design has passed through all stages needed to achieve an optimized electrode design.

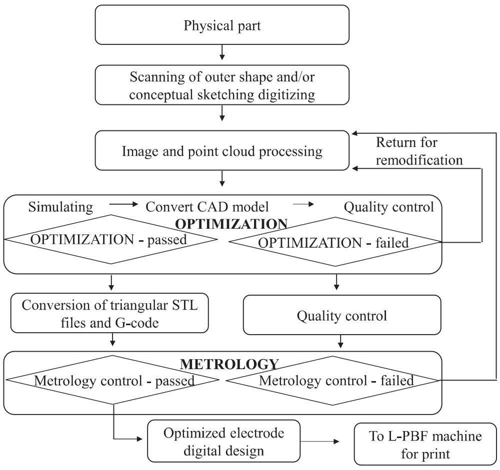

Fig. 8. Schematic of reverse engineering and AM to make an optimized electrode for electrochemical applications. Adapted from [2,4,83].

2.4. Materials used for L-PBF metal electrodes

When choosing a material and manufacturing process for an electrochemical application, multiple factors need to be considered. The intended application of the component, e.g., an electrode, has to guide selection of the appropriate manufacturing process and materials. Materials with a high melting point and high electrical conductivity properties are sometimes preferred for electrode parts [84]. Examples of materials used for electrochemical applications include stainless steel, aluminum (Al), titanium (Ti), lithium (Li), sodium (Na) and iridium oxide (IrO_2). Based on reviewed literature, stainless steel is the most used material for making electrodes. In the reviewed studies, this material is either used as a mixture with other materials or as the base material for the electrodes and coated with other material to improve the electrochemical properties. The use of multi-material electrodes can give combined functionality and improved performance compared with use of a single material. The approach can also result in improved cost-efficiency as well as remove limitations regarding material choice for AM metal electrodes [30,49,85–88]. The base structure of an electrode can be built from easily accessible and cheap material and modified with more expensive or difficult to manufacture material on the surface to suit the application requirements [88,89]. **Fig. 9** lists materials used with L-PBF for electrochemical electrodes and effective coating materials.

Fig. 9 presents a breakdown of different metal materials used for electrochemical electrodes. Twenty publications out of the total number reviewed were further analyzed for design complexity, material types and related challenges in using L-PBF for electrodes. The review showed that base materials (in blue) were either used singly or bonded with other materials (shown in red) to form multi-material electrodes in order to improve the electrochemical properties. Classification of selected studies into single, multi, and polymer materials printed for electrochemical cells in the cases considered in this review is shown in **Fig. 10.**

As it can be seen from **Fig. 10**, base materials of electrodes in twenty of the reviewed were built as a single material. Five were built with a multiple material. All electrodes built as single material were post processed with other materials to improve electrochemical properties. The two polymer parts shown in yellow were components of the electrode assembly such as housing case which were also manufactured with L-PBF.

3. Case studies

Practical usage of metal L-PBF manufactured electrodes in electrochemical applications (devices and processes) are presented in this section.

3.1. L-PBF in electrical discharge machining applications

Electrical discharge machining (EDM) is a process for material removal and can be used for machining of materials that have a conductivity of at least 0.01 S/cm [50]. These materials include, for example, ceramics and hardened steels.

Amorim et al. and Sahu and Mahapatra [90] investigated the performances of L-PBF tool electrodes made with pure copper, bronze–nickel alloy, copper/bronze–nickel alloy and steel alloy powders [50] and metal matrix composites of Al, silicon (Si) and magnesium (Mg) (AlSi10Mg) [90] in EDM experiments. The performance of the electrodes was evaluated by material removal rate and volumetric relative wear either with conventionally method [90] or with the different material [50]. Comparatively, the electrodes built with L-PBF from bronze-nickel powder showed the best performance in the EDM process. Overall, the L-PBF manu-

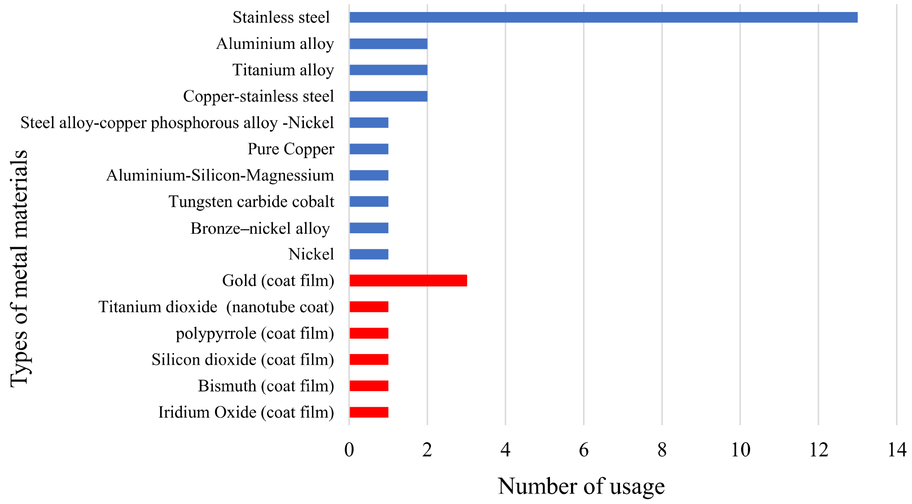

Fig. 9. Breakdown of metal materials used for electrochemical electrode applications based on the review.

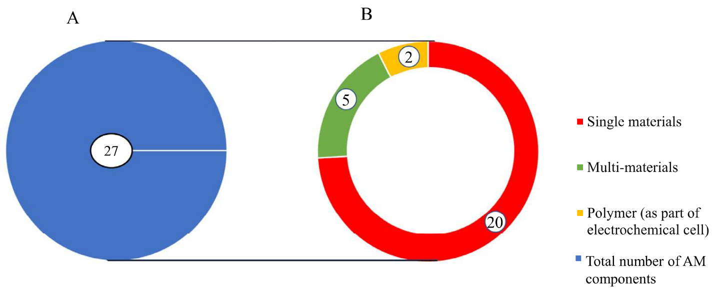

Fig. 10. A) Representation of total number of materials reviewed article. B) Overview of material breakdown into specifics.

factured electrodes did not perform as well as comparable solid copper electrodes.

The results presented in [90] show that the use of L-PBF to manufacture tool electrodes for EDM applications can have a positive effect on manufacturing time and costs. The study also shows the suitability of L-PBF for building tool electrodes for EDM. EDX analysis, however, found traces of the tool on the machined material, which the study attributed to insufficient densification of the tool and wear resistance. Further study is required, particularly, as regards development of materials that are suited for both EDM and L-PBF processes. Other areas requiring further investigation include, for instance, optimization of the process parameters to reduce the porosity of the electrodes, improvement in the EDM material removal rate and reduction in the volumetric relative wear [50]. The machine used in the study was an EOS M 250 [50].

Uhlmann *et al.* investigated the performance of a tungsten carbide-cobalt (WC–Co) tool electrode for EDM fabricated with L-PBF and compared its performance with a conventionally manufactured copper E-Cu 58, graphite EX-75, and tungsten carbide CTS20 tool electrode. WC–Co is “an alloy of a hard ceramic phase, the tungsten carbide (WC), and a ductile metallic phase, the cobalt (Co)” [91]. E-Cu 58 (Cu-ETP) [92] is an “oxygen containing copper which has a very high electrical and thermal conductivity” [93]. EX-75 is a graphite-based material developed as "ultra-low consumption finishing for the electrode for applications such as plastic mold making, mold forging, and die casting moulds [94]. CTS20 is a “submicron grain carbide grade for the universal machining of alloyed and non-alloyed steels, titanium alloys and nickel-based alloys” [95]. Conventionally manufactured EDM tool electrodes have limited process conditions, which can be improved with geometrically complex flush channels designed into the tool electrode. Such enhanced conditions create a challenge to conventional methods used to manufacture electrodes. Some of these process limitations might be absent with L-PBF as this method allows flexible manufacturing of complex-shaped geometries. The simultaneous implementation of flushing channels using special materials like tungsten carbide-cobalt might not be as easy with classical manufacturing methods as with L-PBF. The wear resistance of tungsten carbide-cobalt in the EDM process makes it a favourable option [20]. Processing parameters, such as volume energy density (EV) and build direction can be used to alter the final properties of a tool electrode. An example is given in [20], where low EV was used

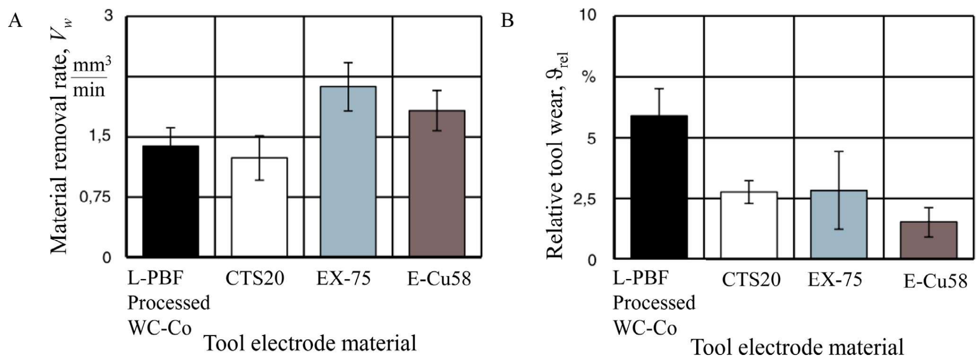

Fig. 11. Performance of tool electrodes manufactured with L-PBF and traditional methods. Reproduced with permission from [20]. Copyright 2018 Elsevier.

with high cobalt 12 wt.% tungsten carbide-cobalt, and high EV with low cobalt 3 wt.% tungsten carbide-cobalt. The performances of the electrodes were compared with conventionally manufactured copper E-Cu 58, graphite EX-75, and tungsten carbide CTS20 tool electrodes. A summary of the performance of the electrodes as regards material removal rate (VW) and tool wear (ϑ) is shown in **Fig. 11.**

As seen from **Fig. 11**, the L-PBF electrodes showed the highest relative tool wear of the four electrodes studied in [73]. Using low cobalt content with high E_V resulted in a poor material removal rate, V_w and high tool wear, ϑ, which was due to low electrical conductivity. The performance of the L-PBF electrode was poor when compared with traditional copper E-Cu 58 and graphite EX-75 electrodes. The *Vw* was almost the same for the L-PBF tool electrode and tungsten carbide CTS20 electrode and both electrodes had lower *Vw* than the compared copper E-Cu 58 and graphite EX-75 electrodes. The material removal rate of the L-PBF and CTS 20 electrodes ranged between 1.20–1.35 mm^3/min. The main reason for this similarity in poor performance is the low cobalt content, which was almost half the values commonly found in industrial tungsten carbide tube electrodes. The low *Vw* with the L-PBF manufactured electrodes was also attributed to high porosity. Hot Isostatic Pressing (HIP) of both the high and low content tungsten carbide electrodes was done to enhance their performance. HIP increased *Vw* and ϑ of electrodes built at low *E* with high cobalt content. The post-processing yielded no effect on electrodes built at high E_V with low cobalt content. The study [20] concluded that using appropriate E_V during L-PBF manufacturing and increasing cobalt content can improve the functionality and quantity of the electrodes as these were identified as potential factors that affected the performance of the printed tool electrode. The identified weaknesses highlight aspects that can be optimized to enhance the characteristics of electrodes.

3.2. L-PBF in substance detection applications

Ambrosi et al. investigated the manufacturing of customized helical-shaped CL 20ES stainless steel electrodes. The tailored electrodes were designed and manufactured in different sizes to suit a variety of electrochemical applications. The study highlighted the versatility and possibilities offered by L-PBF, such as, customization, complexity, and simultaneous manufacturing of multiple parts. Due to the high charge transfer resistance, the printed stainless steel electrodes were surface modified to suit the applications studied. The stainless steel material exhibited slow electron transfer in alkaline solutions, which makes it a poor material for electrodes intended for such environments. This limitation was solved by depositing an IrO_2 film on top of the steel electrode. The functions and properties of the electrodes were characterized by energy dispersive X-ray (EDX) spectroscopy and scanning electrode microscopy. The coated helical electrode showed improved properties such as acting as a pseudocapacitor and evolution catalyst and behaved nernstially as a pH sensor in alkaline solutions **Fig. 12** shows the electrodes designed and voltammograms from the experimental test.

Cheng et al. designed and manufactured a helical stainless steel (iron (Fe) and nickel (Ni) composition) electrode using a Concept Laser machine. The built electrodes were electroplated with gold (Au) for improved electrochemical properties and the performance of the coated electrodes was compared with that of a glassy carbon (GC) electrode. **Fig. 13** shows the CAD model and an optical image of the Au-plated electrode [96].

Elemental mapping analysis of the electrode showed that electroplating can be used effectively to modify the surface functions of stainless steel components by uniform and homogeneous distribution of Au. The electrode designed in the study was used in individual and simultaneous detection of phenol and p-aminophenol (p-AP) using cyclic voltammetry (CV) and differential pulse voltammetry (DPV). Fig. 14 shows a calibration graph of peak current density against phenol and p-AP concentration, respectively.

The results of the study showed that the AM fabricated electrode had higher sensitive and generated intensified signals. The improved sensitivity and signal strength contributed to a higher detection of phenolic compounds. These improvements are due to the efficient electron transfer enabled by the properties of the stainless steel for p-AP detection. However, phenol detection did not show much improvement with the 3D-Au AM built stainless steel electrode as a result of the high rate of adhesion between Au and phenol [96]. Overall, distinct oxidation peaks were observed with the 3D-Au L-PBF electrode. Recommendations to overcome shortcomings that might hinder application of functionally modified AM printed parts as a replacement for conventional electrodes were outlined in the work, one of which is passivation of electrodes used in phenol detention [96].

In a similar study, Lee et al. used L-PBF manufactured electrodes for the detection of heavy metals. Stainless steel was the base material for the designed electrode. The electrochemical properties of the printed electrodes were enhanced by coating the surfaces with either Au or Bismuth (Bi). The modified printed electrodes were applied in individual and simultaneous square wave anodic strip-

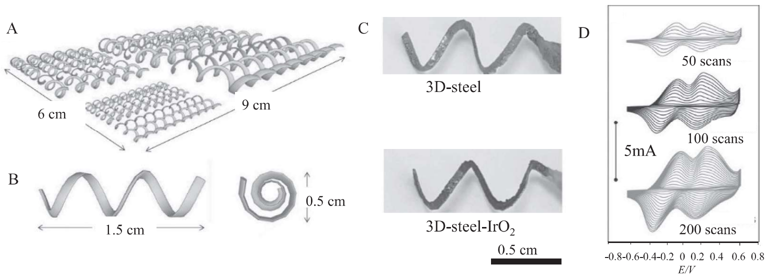

Fig. 12. Schematic of A) the designed model, B) closed view of the model, C) printed electrode with IrO_2 film coat, and D) cyclic voltammograms after 50, 100 and 200 potential scans [31]. Reproduced with permission from [31]. Copyright 2015 John Wiley & Sons, Inc.

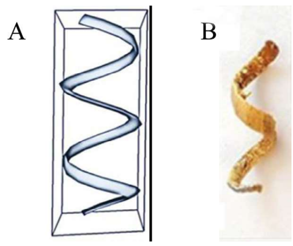

Fig. 13. Representation of A) the 3D model and B) optical image of the Au-plated electrode [96]. Redrawn with permission from [96]. Copyright 2017 Elsevier.

ping to analyze lead (Pb) and cadmium (Cd) in an aqueous solution. The study compared the modified printed electrodes with a conventional GC electrode. The designed and printed electrodes used in the study are shown in **Fig. 15.**

A 50–300 ppb concentration of Pb and 50–500 ppb of Cd were used in the experimental study. For the conditions studied, the printed electrodes showed higher sensitivity towards these heavy metals than a conventional GC electrode, as seen in **Fig. 15**E [97]. Improved sensitivity and selectivity of the electrode material towards heavy metals was seen in the 3D-Au and 3D-Bi coated electrodes.

A high-energy laser beam was used to manufacture stainless steel-based electrodes by Liyarita et al. The electrode was helically-shaped and made from stainless steel powder similar to studies [96,97] using a Concept Laser machine. The surface of the printed electrode was modified by coating it with Au. **Fig. 16** shows the CAD model, as-printed stainless steel electrode and the Au-plated electrode [98].

Varying pulse and cyclic voltammetry were utilized for the detection of dopamine and acetaminophen, both individually and simultaneously. The surface of the Au-plated electrode greatly improved peak currents for both acetaminophen and dopamine. In comparison with a conventional GC electrode, the sensitivity of the Au-plated electrode was enhanced three-fold. The sensitivity of the printed electrode was 4.7 times that of a commercial gold disk electrode [98].

3.3. L-PBF in an EM application

In the ECM process, the anode electrode is dissolved chemically. When metal ions dissolve, they create hydroxides. Hydrogen is produced in the tool electrode. Koyano et al. used a LUMEX Advance-25 machine to L-PBF manufacture a tool electrode for ECM applications. A multi-material composition of 70 wt.% alloy steel, 20 wt.% copper-phosphorous alloy and 10 wt.% nickel powder printed on a LUMEX Avance-25 machine was used for the electrode. The L-PBF process made it possible to create permeable structures, which influenced the functionality of the electrode tool. Different laser

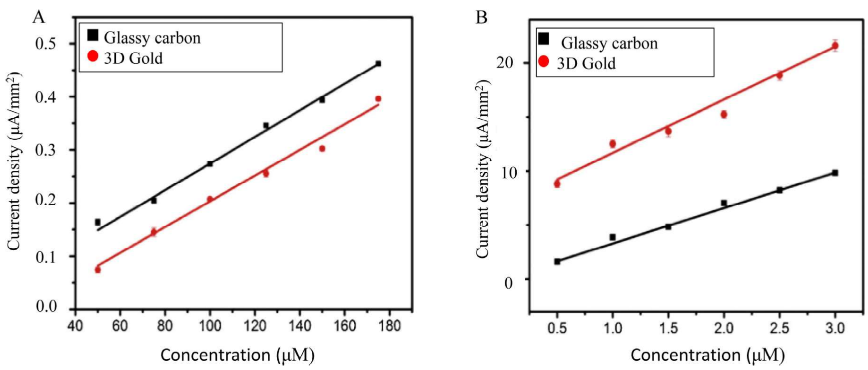

Fig. 14. A) Representation of Peak current density against phenol concentration, B) p-AP concentrations [96]. Redrawn with permission from [96]**.** Copyright 2017 Elsevier.

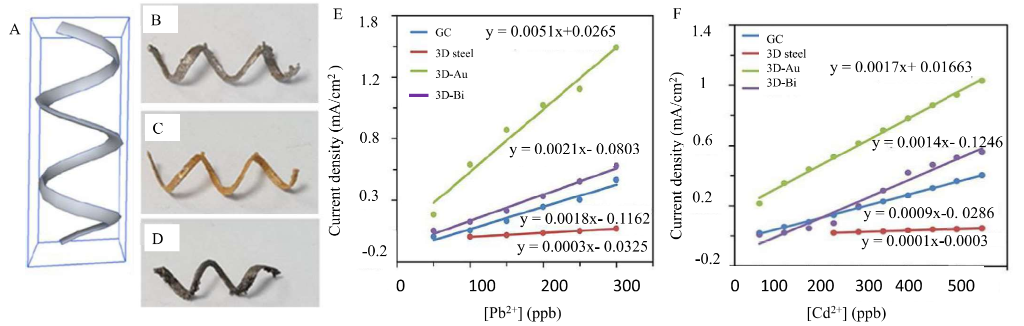

Fig. 15. A representation of 3D model of electrode. B) An outlook of the spiral-like printed steel- electrode. C) Representation of the Au-electroplated electrode. D) Bi-electroplated electrode. E) and F) Representations of calibration curve evaluation using current density as a function of Pb and Cd concentrations of comparable electrodes [97]. Modified with permission from [97]. Copyright 2017 John Wiley & Sons, Inc.

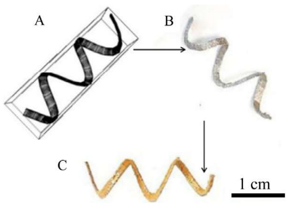

Fig. 16. A) Schematic of the 3D model of electrode. B) Illustration of the L-PBF printed stainless steel electrode. C) Representation of the Au-plated electrode [98]. Modified with permission from [98]. Copyright 2018 John Wiley & Sons, Inc.

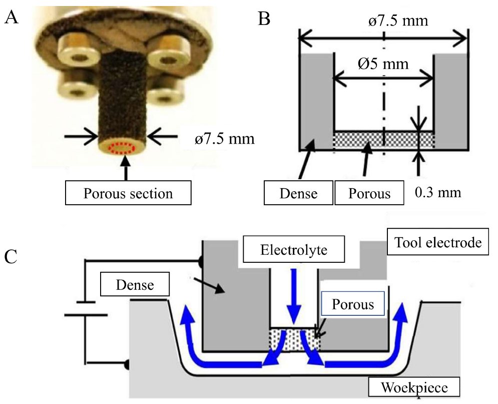

Fig. 17. A) Illustration of the general view of electrode design. B) Representation of cross-sectional view of the studied lattice cylindrical electrode. C) Overview of the ECM process arrangement. Adapted with permission from [49]. Copyright 2017 Elsevier.

scanning speeds with a constant laser power resulted in a variety of pore size and porosity. The electrode tool successfully incorporated small pores with large porosity, which was beneficial for improving the flow rate of the electrolyte, and the L-PBF process was able to produce electrodes without protrusions [49]. **Fig. 17** shows the designed electrode and the ECM process set-up utilized in the study.

The study [49] found that the lattice electrode enabled vigorous flow of electrolytic fluid through the permeable structure. The study also highlighted the benefits of alternation of the positioning of the porous structure with a consolidated part. The L-PBF-manufactured electrode had different porosities and tool geometries that would not be possible with conventional manufacturing methods. Although some conventional manufacturing processes, like micro-EDM, can create small pore sizes, L-PBF offers better performance and more cost-effective production for these electrode tools than classical methods.

3.4. L-PBF for flow reactors

Arenas et al. used L-PBF (M2 Multilaser machine) to manufacture a lattice electrode for electrochemical flow reactors. The electrode was manufactured with stainless steel. The measurements of the electrode and current collector were 60 mm × 40 × 3.7 mm and 68 × 45 × 2.0 mm, respectively. The electrode structure was designed with an internal and hexagonal grid, as illustrated in **Fig. 18**.

The surface area and porosity of the electrodes improved as a result of the scaffold-like structure generated with L-PBF. The use of L-PBF allowed sufficient control of the as-built electrode to eliminate any excessive thermal deformation or internal porosity, which would have resulted in undesirable flow of moving liquid. The integrated model of the electrode and current collector as a single metal unit can avoid corrosion which would otherwise have occurred at weld joints [30]. The stainless steel electrodes were coated with Ni to enhance their electrochemical properties, which improved the performance of the electrodes. The mass transport characteristics were found to be comparable and even superior to mesh, RVS and conventional planar electrodes.

Lölsberg et al. utilized L-PBF to manufacture a metal electrode and polymer housing of an electrochemical reactor. The aim of their study was to improve the mass transport properties of the electrode and the AM electrode was tested in an electrochemical reactor. Stainless steel (X2CrNiMo 17-12-2) electrodes with helical structures were manufactured on an L-PBF machine. The housing of the reactor was built on a Stratasys Objet Eden 260 V polyjet 3D machine with a material jetting technology utilizing a transparent photopolymeric material (Stratasys, RGD810). The electrodes consisted of repeated unit cells with filaments that were oppositely twisted and connected with a single point. Fig. 19 shows the AM-

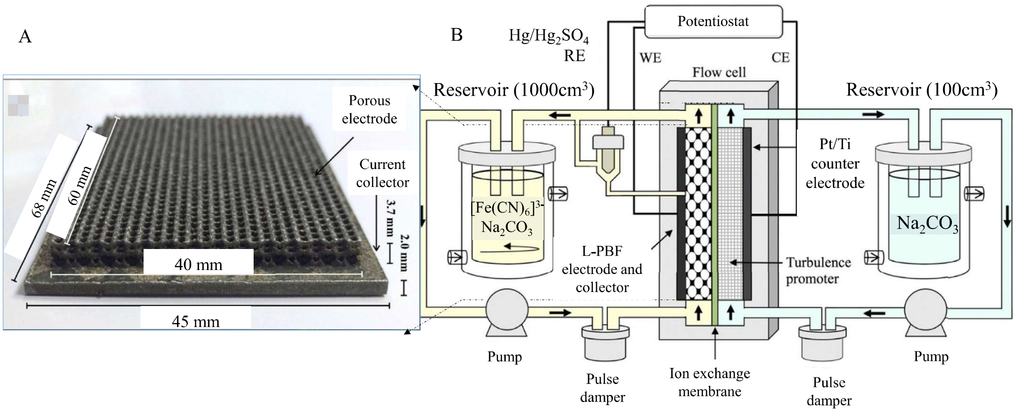

Fig. 18. Representation of A) the 3D-printed Ni/SS lattice structure electrode. B) Representation of the experimental set up used in the flow study [30]. Adapted with permission from [30] Copyright 2017 Elsevier.

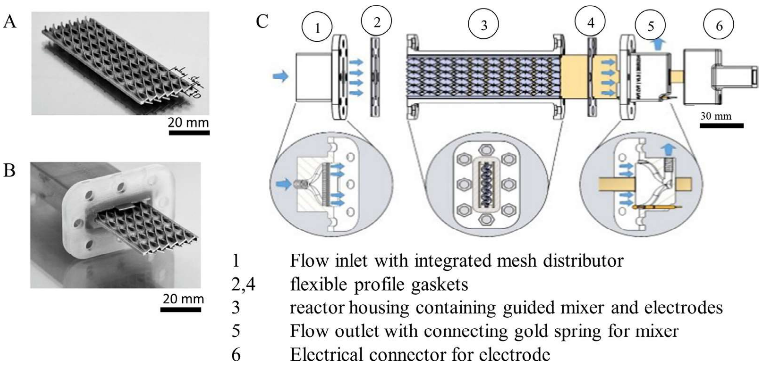

Fig. 19. Representation of A) the helical AM electrode mixer, B) cross section showing the electrode mixer, the upper flat electrode reactor cover, and C) the electrochemical reactor, redrawn from [32]. Modified with permission from [32]. Copyright 2017 John Wiley & Sons, Inc.

printed electrode and a schematic of the electrochemical reactor used in this study [32].

The electrochemical flow reactor was tested under specifically defined flow conditions. Simulations of the fluid dynamics started from the design phase. Dead zones and channelling effects could be avoided by including a mesh in the inlet of the channel, thereby optimizing the conditions for homogenous flow distribution. **Fig. 20** shows the flow field inside the electrochemical reactor [32], where **Fig. 20**A shows the inlet when the flow distributor has not been included, **Fig. 20**B when it is in place, and **Fig. 20**C is the unit cell that is repeated along the flow axes shown in **Fig. 20**D [32].

The study highlights the potential of electrodes that allow flow through mixers. The study combined a high surface area and a mixing effect to reduce potential concentration polarization effects caused by stagnation at the electrode-electrolyte interface. The concentration polarization layer is reduced by use of a helical electrode mixer, which creates a rotational flow profile. When using the electrode in the reactor with a helical mixer, the mass transport coefficient increased by 76% in comparison with a reactor without a mixer. The conducted measurements in this study highlight the benefits that additive manufacturing brings through its ability to create geometrically complex electrode structures [32].

Heiskanen et al. conducted a simulation and theoretical study of the possibility of using L-PBF to manufacture electrochemical metal electrodes for Au recovery. The study aimed to show how this method could be used to make electrodes for recovering Au from waste. Lattice structures were used to achieve high uniform porosity and high surface area [61]. The different lattice structures were simulated to improve chlorine (Cl_2) gas evolution during the Au recovery. The high surface area was considered the most critical factor affecting the performance of three-dimensional electrodes in a flow reactor. Multiple minimum thickness struts were included to enable manufacture of the compact cells with L-PBF. An isotropic lattice symmetrical structure was proposed to improve electrical conductivity and electrolyte flow. A schematic of the designed electrode and a displacement plot of the simulation results are shown in **Fig. 21**.

As **Fig. 21**B shows, L-PBF can be used to fabricate this complex electrode. The use of simulation analysis demonstrated, in a proof-

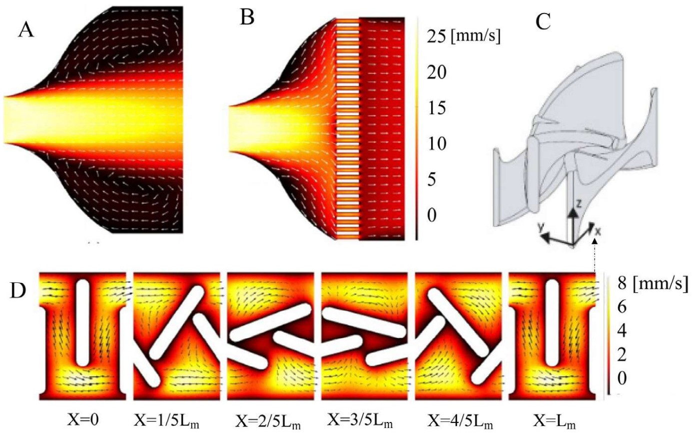

Fig. 20. Representation of fluid dynamic simulation of flow characteristics inside (a) the inlet without a flow distributor, (b) the inlet with a flow distributor, and the electrode mixer visualized by d) six layers along the flow path of (c) repeating unit cells and the direction of flow in the X,Y and Z axes [32]. Adapted with permission from [32]. Copyright 2017 John Wiley & Sons, Inc.

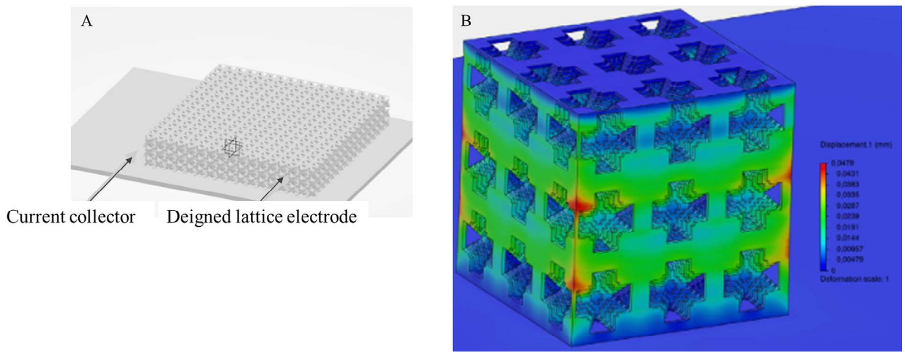

Fig. 21. Representation of the CAD model of an A) integrated electrode and current collector and B) a displacement plot from analysis of the simulation. Reproduced with permission from [61]. Copyright 2020 Elsevier.

of-concept, the possibility of using L-PBF for making symmetrical lattice-structured metal electrodes for Au recovery. Designing the lattice in the electrode enabled the maximum required surface area of the electrode to be achieved. The results in [39] show the potential of L-PBF for fabrication of an integrated electrode with increased surface area, enhanced isotropic porosity and uniform current distribution. These qualities can improve flow characteristics and electrical conductivity.

3.5. L-PBF in water splitting applications

Ambrosi et al. conducted an experimental study to design and manufacture a solid and robust gauze-like stainless steel electrode using L-PBF on a Concept Laser machine. The electrode design was selected for higher catalytic performance due to high surface area. Functional surface modifications of the highly conductive stainless steel electrodes were required to improve the poor catalytic properties towards hydrogen and oxygen. Modification of the surface of the electrodes with either nickel (Ni), platinum (Pt) or IrO_2 enhanced the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). Electrodeposition of films with materials that have desirable capabilities can overcome limitations regarding the materials that can be used [7,99]. **Fig. 22** presents a sketch model, the as-built and coated electrodes.

Energy dispersive x-ray (EDX) analysis of the modified surfaces was used to study the bonding between the printed electrodes and the deposited Pt and the chemical composition. The EDX mapping showed variance in chemical presence depending on the used mode of the electrode. The modified electrodes were directly utilized in water splitting applications since the surface had been altered by electrodeposition with compounds that enhanced electrocatalytic properties towards the evolution of oxygen and hydrogen. The manufactured electrode was used in a water electrolyzer, which was tested in an alkaline solution. The results of the study showed that the as-built electrode had catalytic property, however, the reaction was weaker, and the electrode could not be used as an electrode for water splitting applications. Electrodes modified with Pt and Ti oxide (TiO_2) exhibited better catalytic property to HER than the Ni-modified specimen.

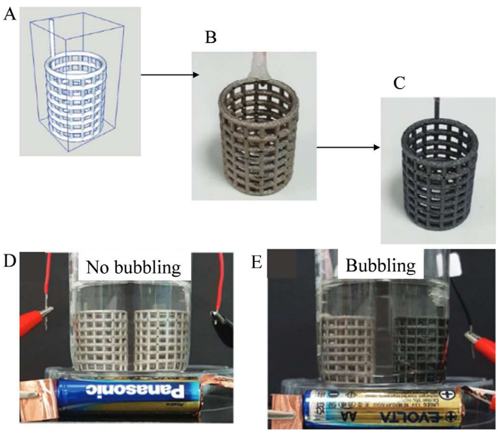

Fig. 22. Representation of A) the 3D model, B) as-printed stainless steel electrode, C) printed electrode with a thin layer of standard catalysts, and the experimental set up using D) the as-printed stainless steel as an anode and cathode, and E) Pt and IrO_2-coated gauze electrodes as a cathode and anode, respectively. Modified with permission from [7]. Copyright 2017 John Wiley & Sons, Inc.

Ambrosi et al. investigated a multi-material based electrode for water splitting. The study utilized two different AM techniques, L-PBF and material extrusion, to print a stainless steel electrode for a PLA electrolyzer cell and separators. The metal and plastic parts were printed using a Concept Laser Mlab Cusing machine and FlashForge Dreamer printer, respectively. The electrode was designed to be compatible with AM cells. The surface of the AM stainless steel electrodes was modified electrochemically to enhance performance in water splitting [48]. Fig. 23 shows a layout of the electrolyzer as used in the experiment.

The anode electrode was electrodeposited with a Ni-Fe film and the cathode with a Ni-MoS_2 film to improve catalytic properties. The overpotential decreased by over 250 mV compared to the plain stainless steel electrodes. The study showed the benefits of combining and integrating different AM technologies in the manufacturing process of functional devices. The study speculated that AM methods may offer a better cost structure for producing functional devices than classical methods [48].

Huang et al. conducted an experimental study with L-PBF to manufacture a 316 stainless steel electrode referred to in the study as a cellular stainless steel (CESS) electrode. The functional requirements of the designed electrode included high porosity, high specific surface area and an interconnected framework for the electrode. The main problem of metal 3D-structures manufactured with L-PBF is difficulty controlling pore distribution, size and geometry. A common consequence of this drawback is unsatisfactory mechanical properties and low electric conductivity of the finished components. Evaluation of the electrodes indicated high electronic conductivity and mechanical strength. The L-PBF CESS electrode also exhibited improved corrosion resistance when tested in an alkaline electrolyte. **Fig. 24** shows the cellular structure of the electrode designed [51].

The 3D printed structure exhibited a large electrochemical surface area and high electronic conductivity and mechanical strength. The electrocatalytic activity was also excellent for the oxygen evolution reaction [51]. 3D lattice-like metals have desirable features in water splitting applications because of their efficiency in electron, ion and bubble mitigation and high electrochemical surface areas. AM can directly manufacture these metal cellular structures, thus removing constraints commonly found when manufacturing electrodes suitable for water splitting and other electrochemical applications such as REBs applications [100]. Conventionally, such foam-like metal electrodes would be manufactured with high temperature sintering. The use of L-PBF to manufacture such electrodes overcomes the poor mechanical strength, due to necking

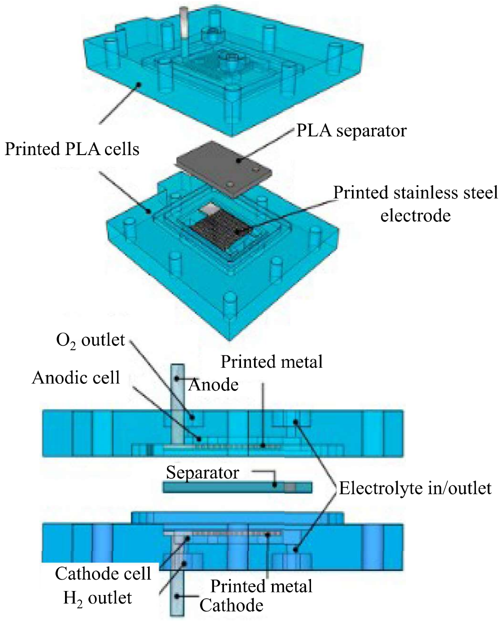

Fig. 23. Layout of components of the electrolyzer unit [48] Reproduced with permission from [48] Copyright (2018) American Chemical Society.

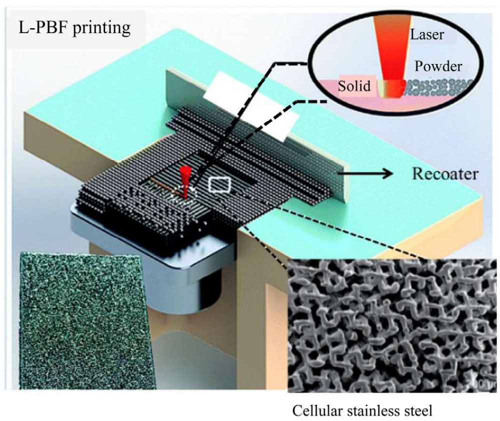

Fig. 24. Representation of the cellular stainless steel electrode in [51], Modified with permission from. Copyright 2017 Royal Society of Chemistry.

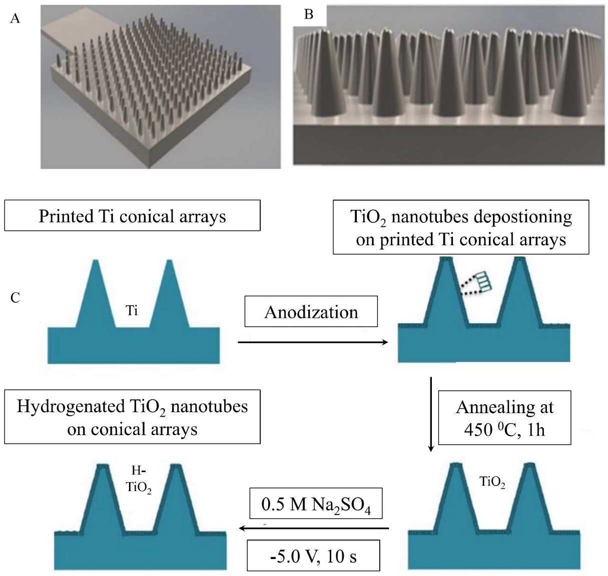

Fig. 25. Representation of Ti conical-arrays manufactured in [101]. A) overview, B) close-up view of conical features of the Ti electrode, and C) the surface modification procedure. Adapted with permission from [101]. Copyright 2017 John Wiley & Sons, Inc.

and the discontinuous construction, which usually characterizes foam-like electrodes produced using conventional methods.

Lee et al. performed an experimental study on Ti-based electrodes with conical arrays manufactured with L-PBF. The aim was to investigate the possibility of enhancing photoelectrochemical water splitting. The printed conical arrays increased the surface area and provided light adsorption. A Realizer SLM50 L-PBF machine was used to manufacture the Ti electrode. High surface area is a requirement for efficient photoelectrochemical water splitting because it improves charge separation and light absorption. AM enables fabrication of conical array microstructures for improved performance of the electrode. Tunable density and size are two of the main benefits that AM brings in the fabrication of micro-conical arrays. TiO_2 nanotubes were applied to the surfaces of the printed electrodes via electrochemical anodization for improved functionality and performance. **Fig. 25** shows the structure of the conical arrays and the surface modification procedure.

As **Fig. 25**C shows, annealing of the electrodes was done to change the amorphous phase to a crystalline phase as a way of attaining an ordered microstructure. In order to improve the electrical conductivity of the TiO_2, further electrochemical reduction of hydrogenated TiO_2 was done on the already annealed conical arrays.

3.6. L-PBF in REBs applications

L-PBF can be used to manufacture electrodes for REB applications using metals such as Al, Li, Na and their sulphides (S^{2-}) or oxides (O^{2-}). Carbon-based materials are required as an active or additive material for almost all existing AM electrodes used in battery applications [47,102]. Batteries may be film-based or structure-based and are used in actuator drives, biomedical sensors and micro-electro-mechanical systems.

Sun et al. reviewed the advantages of enhancing charge transport in electrochemical systems by using AM to make foam-like and ultra-thin electrodes with low mass loadings. The study showed that making electrodes weighing less than 10 mg/cm^2, which is not achievable with conventional methods, can improve performance and offers superior energy or power density. For example, smart micropores and complex structures suitable for improved electrochemical properties can be manufactured with L-PBF [103]. The integration of pores into battery electrodes can contribute to improved ion transport capacity by providing a continuous conductive network for electron transport and a fully interconnected hierarchical porosity [100].

Zhao et al. studied the effect of using L-PBF for the manufacture of Ti-based interlocking electrodes for supercapacitors. The electrodes were fabricated on a Realizer SLM50 metal printer. The material used in 3D printing of the electrode was Ti-6Al-4 V and both the up and down plates measured 1 cm^2. Each half of the electrode was designed to hold vertical pillars of 500 μm by 8 mm diameter. The top plates had 32 pillars, whereas the bottom had 32 pillars. The L-PBF manufactured electrodes offered enhanced surface area. The vertical pillar surfaces of the top electrode were plated with polypyrrole (PPy) to create an electroactive surface. The areal energy density was found to be three times higher for the PPy-coated electrode (2.98 × 10–6 Wh cm-2) than a comparable planar electrode (0.92 × 10–6 Wh cm-2). Capacitance retention of 90% and 75% was recorded for the coated electrodes, measured at a current density of 14.98 mA cm3 after 500 and 1000 cycles. About 56% capacitance retention was achieved with the improved PPy-coated Ti-6Al-4 V electrode [104]. **Fig. 26** shows the designed electrode and the approach used to electrocoat the electrode.

The active-passive state of L-PBF manufactured Al alloy ($AlSi_{12}$) electrodes on a ProX® DMP 200 machine was evaluated by Chiu et al. The study found that L-PBF manufactured $AlSi_{12}$ alloy electrodes had better passivation than conventionally cast electrodes of

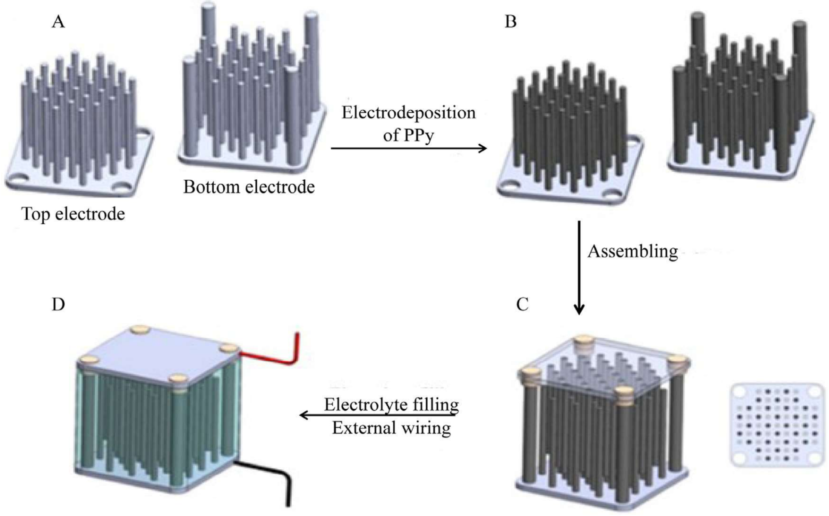

Fig. 26. Schematic of the A) as-printed top and bottom electrodes, B) PPy-coated electrodes, C) assembly of Ti electrodes to top and bottom plates, and D) the experimental setup. Reproduced with permission from [104]. Copyright 2020 Elsevier.

the same materials, which enhanced the corrosion behavior of the AlSi12 electrodes. The layerwise manufacturing of the electrodes improved the corrosion behavior of the L-PBF manufactured $AlSi_{12}$ alloy electrodes by enabling the incorporation of an amorphous passive layer of fine columnar Al grains in the silicon networks [105].

Jha et al. conducted experimental study to investigate the morphology impacts of L-PBF manufactured electrodes in rechargeable Li-ion batteries. The electrodes in the study were manufactured of Al alloy on a ProX DMP 200 L-PBF machine. Amorphous silicon dioxide (SiO2) nanoparticles were added as active material (with 70–90 wt.% of Al, 10–20 wt.% of Si) to the as-printed lattice structure electrodes in rechargeable Li-ion batteries. The SiO_2 nanoparticles were added to the as-printed lattice structure $AlSi_{12}$ as the outer layer by the Sol-Gel method to increase the charge capacity of Li-ion battery. The deposition of SiO_2 nanoparticles on an $AlSi_{12}$ structured composite electrode theoretically resulted in an increased surface area of the electrode. The pore sizes measured by 3DXpert manufacturing software for the small, medium, and large pore size electrodes were 2000 μm, 2500 μm, and 3000 μm, respectively. The non-coated cubic lattice structure electrode increased the non-Faradic current at the maximum voltage value in comparison to a solid electrode. The higher current can be ascribed to the greater surface area provided by the lattice structured design. In addition, the authors attributed the higher surface area indicated by the shift in the non-Faradic region to better electrolyte-electrode electrochemical reactions in the battery cell.

In addition, the electrode activated with the SiO2 nanoparticles raised the intercalation of Li ions from the electrolyte to the target electrode. The enhanced capacity in the CV curve of the LC, compared to the phase transformation characteristics of the non-porous electrode could be a result of the presence of pores. No capacity retention was observed for the electrode without active material. The non-Faradic current was minimized also by the active material (SiO2). The pore geometry, morphology, and pore distribution had an impact on the performance of the electrode by distributing active material mass. For instance, on the one hand, the 2000 μm pore electrode provides higher specific capacity than that of the 2500 μm pore electrode, whereas the 3000 μm pore electrode contrarily had the highest specific capacity. Therefore, the kinetic diffusion and ion transport from the electrolyte into the active material can be influenced by pore size and mass distribution of the active material. The presence of pores with no active material deposition (non-coated) in the cubic porous electrode raises the non-Faradic current by a factor of two (at the highest voltage value) relative to that of an electrode with no pores at all. AlSi12 composite material was introduced as an ideal choice for the 3D-printed electrode. The advantage of using L-PBF is based on the high temperature of the manufacturing process, which prevents oxidization of the electrodes. This study identified areas for future research in kinetics reactions in open-lattice hierarchically structured AM electrodes.

4. Results and discussions

In this study, various research papers about the utilization of L-PBF in the manufacturing of electrodes were reviewed. The research was limited to metal electrodes for use in electrochemical cells. The aim of this study was to identify the benefits and opportunities that L-PBF provides in the manufacture of components for electrochemical applications. Several of the reviewed articles are laboratory studies and do not report potential industrial benefits. Further research is thus needed to ascertain the relevance of the presented findings to commercial application.

The review shows that many different materials and alloys can potentially be printed on L-PBF machine systems. Stainless steel was found to be the most used material for electrochemical applications. This review also found that L-PBF can be used to manufacture multi-material electrodes and electrodes with various pore sizes. Many of the studies reviewed highlight utilization of L-PBF as a viable technique to manufacture intricate electrodes with optimized characteristics, for example, coarse surfaces and optimized

Table 1
Summary of the research case studies.

Application	Materials and characteristic	Results	Challenges	Ref.
EDM tool electrode	• Bronze-nickel alloy. • Pure Cupper (Cu) (□50 μm). • Stainless steel alloy (DS20 (□20 μm). • Mixture of 50 vol% pure Cu and 50 vol% standard EOS steel alloy. • AlSi10Mg. • Tungsten carbide cobalt	• A complex flush channel was designed. • The bronze-nickel powder showed the best performance. • Less time and costs in manufacturing.	• The electrodes did not perform as well as the comparable solid copper electrodes. • Insufficient densification of the tool and wear resistance. • Optimizing the process parameters to reduce the porosity of the electrodes. • Controlling of *Ev* during the L-PBF may not easily be controlled with certain materials.	[50] [90] [20]
Substance detection	• Stainless steel plated with iridium oxide (IrO2) film. • Stainless steel gold (Au) plated. • Stainless steel coated with Bismuth (Bi). • Stainless steel Au coated. • Stainless steel Au plated.	• Sensitivity to phenol and p-aminophenol (p-AP) detection was obtained. • Au plated electrode improved both acetaminophen and dopamine detection. • The sensitivity of Au plated electrode was increased by 4.7 times.	• Stainless steel electrode is a poor material for applying in alkaline solutions. • The Au -plated AM stainless steel electrode showed a weak performance for phenol.	[31] [96] [97] [98]
ECM	• Powder mixture (70 wt.% alloy steel (42CrMo4). • 20 wt.% Cu-Tin alloy (CuSn8), 10 wt.% Ni).	• L-PBF built lattice-like electrodes offered a vigorous flow for electrolytic fluid. • Optimized lattice structures enhanced electrode performance. • Electrolyte flow rate for increased machining rate were improved with optimized L-PBF electrodes	• Flow marks appeared to form on the machined surface. When the gap width was wide due to cavitation and the difference in the electrolyte flow rate. • Further experimental studies on the electrolyte flow rate is needed to control the area of the lattice structure.	[49]
Flow reactors	• Stainless steel) Ni coated. • Stainless steel (X2CrNiMo 17–12–2).	• Scaffold-like structure comparable and offered better functionality, RVS and conventional planar electrodes to improve mass transport. • The surface area and porosity of the electrode were enhanced. • The continuous manufactured model of the electrode and the current collector as a single metallic unit using AM controls the corrosion probability compared to the welded joints. • Due to a rotational flow profile, concentration polarization effects were minimized in the transport limited reactions. • The mass transport coefficient was increased by 76%. • The possibility of the symmetrical lattice structured manufacturing was approved by simulation analysis.	• No experimental studies were performed to explain how the scaffold AM structure could enhance the surface area, porosity, and controlled corrosivity of the current collector and the patterned structure. • The material selection as a critical item could be focused on future research.	[30] [32] [61]
Water splitting	• Stainless steel (CL 20ES) coated with Ni film. • Stainless steel (CL 20ES) • coated with Pt film. • Stainless steel (CL 20ES) • coated with IrO2 film. • Stainless steel. • Stainless steel coated with Ni-Fe film. • Stainless steel coated with Ni-MoS2. • Stainless steel (316 L stainless). • Titanium (Ti), with TiO2 nanotubes.	• Micro-conical arrays Ti electrode increased anodization performance. • L-PBF allowed controlling of pore distribution, sizes, and geometry than CM electrode. • Improved mechanical properties with L-PBF electrodes. • An L-PBF built cellular stainless steel (CESS) electrode improved corrosion resistance with electronic conductivity, and mechanical properties in an alkaline electrolyte.	• Weak catalytic property was seen in the L-PBF stainless steel electrodes.	[7] [48] [51] [101]
REBs	• Ti (Ti6Al4V) coated with	• L-PBF electrodes enhanced charge	• Gap in literature on the	[100] [104] [105]

shapes such as lattice zigzag configurations. The ability to design electrodes with such geometries can enable cost-effective electrochemical processing due to the enhanced efficiency of the electrodes.

One objective of this review was to ascertain the state-of-the-art of knowledge about the use of L-PBF for the manufacture of electrodes for Au recovery. However, the review, did not find existing studies that directly examine the application of L-PBF for manufacturing of metal electrodes for gold recovery in spite of many potential benefits. The only existing studies of L-PBF for Au recovery in the literature were polymer based [43,72]. A clear gap in the literature exists as regards investigation of the utilization of L-PBF for manufacturing of metal electrodes for Au recovery.

The advantages of using multi-materials for electrodes are improved functionality and reduced cost, as cheaper materials can be used as base material and coated with more expensive material. Stainless steel, for instance, can be printed in complex shapes to form the base of the electrode, which will improve mass transport properties, and can be surface modified with Au or SiO2 nanoparticles to achieve enhanced electrochemical performance. A summary of the case studies reviewed giving the results achieved and challenges encountered because of either the L-PBF process or the materials used is presented in Table 1.

Conclusions

This study reviewed papers investigating the applicability of L-PBF to produce metal electrodes for six types of electrochemical applications, namely, electrical discharge machining (EDM), substance detection, electrochemical machining (ECM), flow reactors, water splitting and rechargeable batteries (REBs). The studies reviewed were related to utilization of AM of metal electrodes used in electrochemical processes. This study evaluated cases of L-PBF in the selected application fields in terms of design and types of metals materials for electrochemical electrodes. The study has shown that there are not many studies about the utilization of L-PBF for the manufacture of electrodes for electrochemical applications. Moreover, many of the existing studies focus on theoretical aspects, thus, more experiments are needed to assess the potential benefits of L-PBF in industrial sectors.

The review demonstrated the potential benefits of L-PBF as regards optimization of electrode shape, cost and performance. L-PBF manufacturing enables optimization of the mass transport properties of electrodes and permits design of complex geometries able to reduce flow resistance. The production of complex designs is not straightforward when using conventional methods. Component size are limited according to size of build platform. L-PBF is limited by need of support structures which can increase production cost if not well planned with the right use of simulations and DfAM guidelines.

The industrial relevance of this article is that it illustrates the potential benefits and drawbacks of using L-PBF to produce components used in electrochemical applications. The use of L-PBF will enable industries to integrate features such as lattice and tortuous structures into electrochemical equipment to produce functionally complex electrodes without increasing cost. A further benefit is that L-PBF can be used to manufacture tailored metal electrodes that can be coated with functional materials to suit specific functions. The use of L-PBF can enhance the sustainability score of industries. Lasers-driven fusion is light-based energy which are energy efficient as they do not generate greenhouse gas emissions (GHGs) [107,108] on the manufacturing phase thus has low environmental impact. Nevertheless, a comprehensive lifecycle analysis may show the electrical power and materials used in the process may contribute to GHGs by means of sources of energy and type of releases.

The main contributions of L-PBF in manufacturing of separation units for electrochemical applications are:

1 Effective application L-PBF can remove design limitations in electrode design thus improve electrode performance.
2 The use of simulation driven software can enable creation of optimized and energy-efficient electrodes for enhanced part functionality and cost-effectiveness.
3 L-PBF allows different metal powders to be combined for a single part with tailored component characteristics.
4 Functional electrochemical materials can be bonded effectively to metal AM electrodes to improve performance and cost efficacy.

Few articles can be found in literature that investigate L-PBF electrodes and almost all the studies are based on prototypes. Thus, there is insufficient data for reliable analysis to assess industrial use. Moreover, no empirical studies about Au recovery with metal-based printed electrodes have been presented. Therefore, it would be important to continue study of L-PBF and manufacture of metal-based electrodes for Au recovery.

The studies reviewed show that L-PBF manufacturing has considerable potential for the production of components used in electrochemistry and demonstrate that L-PBF can offer benefits such as improved efficiency, lower production costs, greater freedom in parts design, and enhanced parts optimization for specific applications. Further studies must consider the manufacturability and performance of electrodes for Au recovery.

Declaration of Competing Interest

None.

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