The economic sustainability of Spheroidization of Ti6Al4V with respect to Additive Manufacturing: Literature Review

Tsepo.M. Dube[1*]
[*1] Department of Industrial Engineering
University of Stellenbosch
Stellenbosch, South Africa
tseposmdubes@gmai.com

Hertzog Bissett[2]
[2] Research and Development,
South African Nuclear Energy Corporation SOC Ltd,
South Africa,
hertzog.bissett@necsa.co.za

Stephen Matope[3]
[3] Department of Industrial Engineering,
University of Stellenbosch,
Stellenbosch, South Africa,
smatope@sun.ac.za

Andre F van der Merwe[4];
[4] Department of Industrial Engineering
University of Stellenbosch,
Stellenbosch, South Africa
andrevdm@sun.ac.za

Abstract

Additive Manufacturing has been slowly introduced to the commercial sector. The technology is also rapidly improving to improve the quality output of the products produced from Additive Manufacturing. The economic aspects of Additive Manufacturing are crucial if Additive Manufacturing is to constantly grow. The economic sustainability of Additive Manufacturing currently depends on the batch size manufactured. The study will show the extent which the economic sustainability of spheroidization of Additive Manufacturing metals has been covered by studies. The success of Additive Manufacturing depends on the powder production process, the printing efficiency and the efficiency in the recycling of the powder itself. In South Africa many researches published focus on the selective laser melting process and recently the recycling of Additive Manufacturing material has been introduced. In the research United States of America and Germany were the territories used as cases studies because they are the industry's leaders.

Key words
1. Economic Sustainability
2. Additive Manufacturing
3. Economic viability

1 Introduction

The study was done for Necsa (South Africa Nuclear Energy Cooperation SOC Ltd.). Necsa has a spheroidization plant and there is a need to determine if the process is economically viable and sustainable. In the literature in was found that there is a gap in studies pertaining to economic viability of spheroidization of metal powders and thus the research was readjusted to include additive manufacturing (AM). The researchers intended to determine the economic viability of spheroidization in South Africa and the extent to which researchers have studied it around the world. The initial search to determine the economic viability of spheroidization yielded no results. The research was then altered to determine the extent which economic viability studies have been conducted for AM. This was done to find out the gaps in AM in terms of economic viability studies in order to identify the gaps that future researchers can fill. AM has not fully penetrated industry because there are few studies that highlight its economic sustainability, so there is need to conduct more research on the economic sustainability (Arbabian, Wagner and Foster, 2020) (Oyessola *et al.*, 2018) (Pannitz and Sehrt, 2020). The research will also help the research team at Necsa ascertain the extent to which the economic sustainability of AM has been conducted. This will help also find out the extent spheroidization of titanium alloy can be economically beneficial to additive manufacturing.

In the research few countries where analysed in relation to South Africa. The two countries studied were USA and Germany. These two countries where chosen because they are the industry leaders in AM to date. These countries can give a bench mark for the South African industry which it can follow. AM is economically sustainable but the extent of its sustainability still needs to be measured at every stage of the AM value chain. In South Africa the AM process is considered economically sustainable (Oyessola *et al.*, 2018). The area that needs more research is the reconditioning of the AM material. The reconditioning can be done through spheroidization at Necsa. The process has the potential to make the AM process economically sustainable but there are still few studies that prove its economic sustainability. Two important definitions were given to give an understanding of the topic researched on.

Important Definitions

1. **Additive Manufacturing**

Additive manufacturing (AM) is manufacturing which involves manufacturing parts in layers.

2. **Spheroidization.**

Spheroidization is the process in which metallic particles are passed through a thermal plasma to rapidly melt and quench particle with the aim to reshape them to spherical shapes. Spheroidization is used to return used AM material to spherical particle shape.

1.1 Economic sustainability

Sustainability is divided into three sectors which are environmental, economic and social. Figure 1 shows the 3 facets of sustainability (Gao, Wolff and Wang, 2021a). Economic sustainability is the main focus of the study which encompasses

1. Economic growth
2. Efficiency and competitive ness
3. Flexibility and stability
4. Production and consumption
5. Trade
6. Employment.

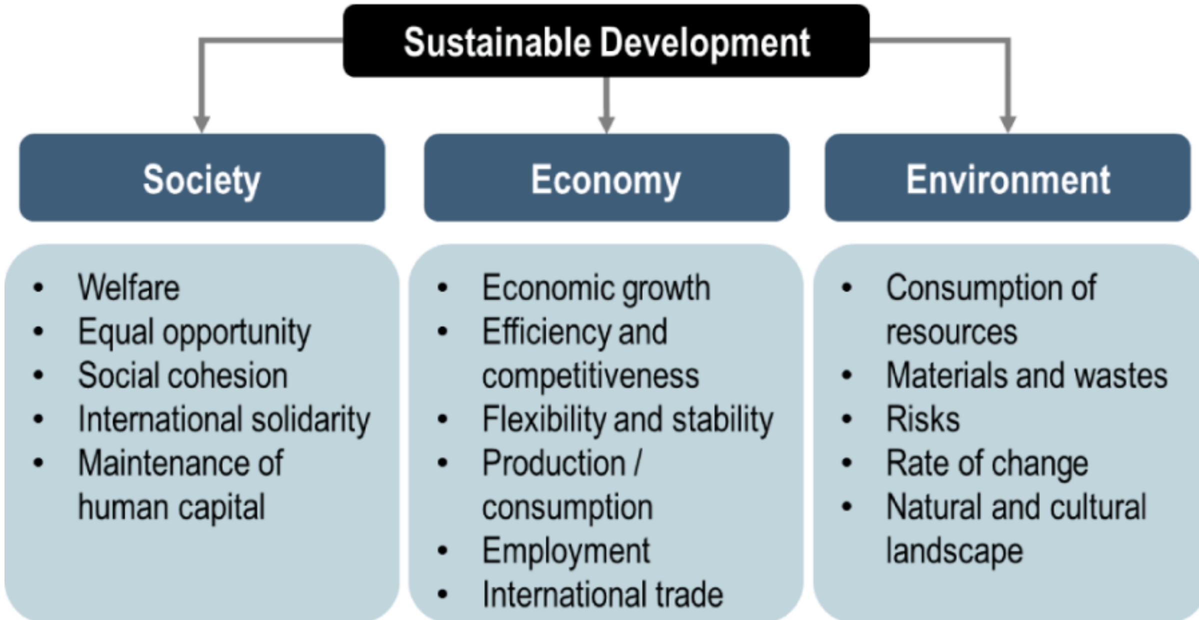

Figure 1: Sustainable Developments

The review was done to find articles that satisfy the definition of economic sustainability in AM. Economic sustainability is a method of sustainability that ensures using finite resources in order to ensure the resources are available for future generations. In economic sustainability the financial aspects of a project are also evaluated and integrated into the sustainability matrix. For economic sustainability resources must be safe guarded and used sustainably. The economic sustainability in AM is dependent on the batch size (Attaran, 2016).

The topics and discussed that are in line with economic sustainability of AM are

- Decentralisation of manufacturing
- Disruption of the supply chain
- Recycling through spheroidization
- Making of light weigh parts

The initial research focus was spheroidization but there is currently little data on the economic sustainability of spheroidization of metal powder. The review was expanded to find out the gaps in AM economic sustainability studies. Sustainability assessments have been done in previous studies for additive manufacturing but few none have been found directly related to spheroidization and reconditioning of AM metals (Jiang *et al.*, 2019) (Nagarajan, Raman and Haapala, 2018) (Ma *et al.*, 2018) (Godina *et al.*, 2020). Spheroidization of AM material can bring about economic sustainability of AM by reusing AM material.

2 Methodology

A systematic literature review was used for the research. A systematic review is a review of a formulated research question that uses systematic and repeatable methods to identify, choose and critically appraise all relevant research. In a systematic literature review, information is collected and analysed from selected articles (Crocetti, 2016). A systematic review aims to answer a research question and critically analyse the data. The steps taken to conduct the research were:

1. Identify the research topic
2. Identify the research question
3. Identify the search terms to be used
4. Identify inclusion and exclusion criteria
5. Identifying relevant work within the studies
6. Assessing the quality of studies

7. Extracted the relevant data from included studies
8. Present results and assess the quality of evidence

Research Aim
1. To find out the extent which literature covers the economic sustainability of spheroidization with respect to AM?
2. To find out the extent techno economic studies have been done on AM.
3. To give an insight of the economic benefits in AM.

Scopus and Web of Science were used to for the research.

Screening
The primary search terms are
1. Additive Manufacturing
2. 3D printing

The secondary search terms were
1. Economic sustainability
2. Economic viability

The search was also limited to
1. 2017-2021 so that only resent research is considered.

The initial topic identified was Economic sustainability of spheroidization; however, there is still little research done on the topic. The research was then broadened to include AM as a whole. This was done to identify the gaps that are present in AM and also to identify were spheroidization can fit into the economic sustainability of AM. The research question was structured as follows:

To what extent has economic sustainability studies been carried out for spheroidization with regards to AM?

2.1 Selection criteria
Only articles with topics related to AM were selected. Within the abstracts and titles, the terms selected were AM, selective laser melting and 3d printing. Topics not related to metal AM were excluded. The AM technologies excluded were stereolithography, selective laser sintering, fused deposition modelling and inkjet printing. Within the topics related to metal AM only articles related to economic sustainability of AM were sought after. The articles had to include economic viability, economic sustainability, and economics of AM and economic benefits of AM. If these terms were not within the abstract or title of the articles, the researchers would read the article to find out if it was related to economic sustainability of AM. If the article met the criteria, then it would be selected.

Various countries have adopted AM and but the researcher choose three countries to analyse. These countries are United States of America, Germany and South Africa. The aim was to compare how South Africa fares against first world countries in the adaptation of AM and its profitability. The selected articles were to meet the following conditions.

1. The articles were selected if they included AM in their topics, abstracts or keyword.
2. The articles had to contain an economic sustainability related topics or abstract.

There were other articles outside of the review which were included for review in the research to provide a wider overview of the economic sustainability studies.

2.1.1 Selection of countries
United States of America, Germany and South Africa were chosen as case studies. The reason for choosing America and Germany are that they are the AM industry's leaders in their continents and worldwide. America dominated the AM market share with more that 35% of installed AM machinery (Wolhers 2019). In the USA, the military also has adopted AM technology. In the USA, the military and aerospace are the dominant players in adaptation of the AM

technology. Most of the investments are in the private sector. USA was also selected because it is the biggest economy in the world.

Europe has the second highest market share in the AM sector though they have the most companies that practice AM. The reason for choosing a western European country for analyses and comparison is to gain an understanding of the extent South Africa has adopted AM with respect to leading industry players. In Europe the biggest challenge in adaptation of AM is skill shortage (Giffi, Gangula and Illinda, 2014). More training is required for adaptation of AM technology. From Europe Germany was then selected for the study. Germany manufactures many of the AM machinery and it is a good benchmark to follow when measuring the economic sustainability of AM. Italy, England and France are also major market share holders in the AM industry. In the European Union, Germany is the largest country and also the largest adopter of the AM technology. It has more than 148 research institutions, with Fraunhofer Research being the biggest (Nahirna, 2019), researching on AM. South Africa is part of the study because the Necsa is the case study for the research which is located in South Africa.

2.1.2 Scopus Search

Compared to the AM industry leaders, South Africa is still lagging behind as reflected in the publications researched. A search on AM was done and 41872 journal were found with the following distribution shown in Table 2.

1. 12173 were America
2. 4287 were Germany
3. 362 were South Africa
4. 25050 were other countries.

Table 1: Scopus Results

Search term	Result For Additive Manufacturing	Relevant Results For Economic Sustainability From 2017 -2021
America	12173	124
Germany	4287	51
South Africa	362	9
Other Territories	25050	N/A

The results were limited to from 2017-2021. The search was refined to economic viability to find out the extent which researchers are focusing on the economic viability aspects of AM and the following information was obtained:

1. America 124
2. Germany 51
3. South Africa 9

2.1.3 Web of Science

With Web of science the results yielded fewer articles. The other advantage with Web of Science is that the results were more stream lined and did not require a lot of screening to find relevant journals. The disadvantage is that separating results according to territories is not as simple as in Scopus. When additive manufacturing search 41867 results were found. When the search was refine to economic sustainability 94 results were found and 52 of these were relevant to the research. There was no need to separate the Web of Science Articles as it would be repetition of the Scopus search.

The articles were from Scopus and Web of Science were all mostly the same and thus the outliers were simply included in the results. The relevant papers were further analyse to find out more information on the publication trends in AM sustainability.

2.2 Economic viability

Apart from the economic sustainability the researchers also discovered that there were some research articles that also focused on the economic viability of AM so the researchers decided to review and define the economic viability with respect to AM. The economic viability of a project can help decide if a project is worth pursuing. If the benefits of the project exceed its economic costs, then it is considered economically viable. The economic costs may go beyond the financial investments in the projects which may include the benefits to the environment. The economic benefits may cover aspects and people who are not directly involved in the projects (Trentin, Adamczuk and Batistus, 2015). Reconditioning has many potential economic benefits especially in the AM sector though there are no studies that document the benefits.

Among these are
1. Reconditioning may reduce the rate of extracting more titanium from the ground thus cutting down the processes that feed into purifying titanium.
2. If energy used in reconditioning is less than the energy in making virgin powder, then energy saving are realised in reconditioning.
3. Energy savings in an economy mean less extraction of fossil fuels required to create the energy (Murray *et al.*, 2019a)
4. With much of the titanium powder exported, reconditioning benefits the economy by reducing the need to import titanium powder.

To the AM industry, the reconditioning process is potentially economically viable especially in South Africa. Reconditioning Ti6Al4V is a steppingstone to ensuring that the South African industry is independent from other countries that manufacture Ti6Al4V powder.

For economic viability the factors to consider are:
1. The cost of the project
2. The potential to secure funding
3. The profitability over the lifetime of the project
4. Positive impact in community and job creation
5. Flexibility of technology to adjust to future changes.

The economic viability and sustainability of AM process has 6 publications that directly mention the economics of AM.

The systematic literature review yielded no results for the economic viability of spheroidization research in South Africa. However, there are ongoing studies that are investigating the economic benefits of spheroidization. The economic sustainability of spheroidization depends on the material spheroidized though there are not many studies on the economic benefits for specific materials. The materials used in AM are expensive and difficult to extract, thus need to be used sparingly. Reconditioning ensures that little material is wasted in the lifecycle of the material
(Bao *et al.*, 2021)

. The most common material in AM is Ti6Al4V.The material cost is quite high and thus needs to be used sparingly with little waste as possible.

Although the reconditioning process has a high investment cost, the process in the long run has a high potential to improve the economy of the country. Currently a few publications are available on spheroidization economic viability of which most that are available partly address economic aspects of spheroidization. The search was then broadened to include AM as a whole to find out the gaps in economic sustainability studies in AM. There are few publications that address the economic sustainability of AM. AM has been shown to have economic advantages for small production volumes and complex designs (Dircksen, Dircksen and Feldmann, 2020).

Before an organisation can take up a new technology, the usual action is to compare with conventional technology. Normally AM is compared to conventional manufacturing that includes subtractive manufacturing, casting and forging. Studies highlight that the economic sustainability depends on the volume produced (Jiang, Kleer and Frank T Piller, 2017). The economic Viability of AM was reviewed from a Germany, American and South African perspective.

2.2.1 United States of America (USA) Perspective

America has the most publications on the economic benefits of AM as a whole. As an industry leader in the manufacturing sector worldwide, USA also leads in the AM sector. Cost analyses of stereolithography have been done and it has been highlighted that there is still more to be done in other AM technologies (Günther *et al.*, 2017). The lack of universal standards is what makes AM difficult to adopt in USA. Though AM has some economic benefits, there is still need to develop universal standards for America to adopt AM.

With various technologies available, different process parameters to administer AM on materials may cause different manufacturing standards. There is need to develop standard operating procedures for AM which can ensure consistency even with different AM technologies. With regards to AM being economical, energy consumption is also an area that researchers are focusing on (Gutierrez-Osorio *et al.*, 2019)(J. Jakob Heinen and Hoberg, 2019) (Hettesheimer, Hirzel and Roß, 2018a). Energy consumption is an important part of the manufacturing phase as it can determine if it is economical or not. It is also important that researchers also analyse and study each phase of the AM process to give a clear over view of the energy consumption at the respective phases (J. Jakob Heinen and Hoberg, 2019).

The material efficiency of AM is also attractive in the USA. A gap that was highlighted in literature is the need to include the energy needed for the production of the AM material, as this can give a holistic view of the economic benefits of AM (Huang *et al.*, 2015). These processes may include the atomisation of metal and spheroidization of metal. It is however, important to note that AM is not always more efficient than conventional manufacturing. There is need to develop an instrument that can help choose the right process for different scenarios in manufacturing. Subtractive manufacturing can be more energy efficient, can consume less material in cases where little material is removed to make a curtain part (Huang *et al.*, 2015) (Marcus A. Jackson *et al.*, 2018). AM also maximises energy consumption through nesting of parts thus building multiple parts in a single build (J. Jakob Heinen and Hoberg, 2019) . This reduces idle time in build set up which would still consume energy through keeping machinery running. In subtractive manufacturing there is a lot of idle time during which energy is consumed in keeping machinery running which may include the motors or spraying of coolants (Jiang *et al.*, 2019). A problem identified with AM standardisation is that while the energy consumption can be measured for a specific part, the results are not easily transferable to other parts which then need to be measure again. More research also needs to be done to develop a method to predict energy consumption across different technologies in AM and for different part designs. This can also make it easier to determine the economic sustainability for specific AM processes and components (Jiang *et al.*, 2019). The parameters that will need to be optimised are laser beam properties (power, scan rates electron beam power, powder bed temperature). These parameters vary across different parts.

Considering only the AM itself is not enough to provide a holistic overview of the economic benefits of AM. Considering the whole life cycle of AM is also important (Hettesheimer, Hirzel and Roß, 2018a). Considering the cost and energy consumed in the production of the feed wire to the atomisation process is also important (J. Jakob Heinen and Hoberg, 2019). There are also logistical factors which also include labour and transport which also need to be accounted for (Arbabian, Wagner and Foster, 2020). In the spare parts manufacturing, AM can come in handy. Manufacturing plants can be brought closer to the customer, thus there is energy savings provided batches manufactured are big enough to justify decentralisation of manufacturing (Arbabian, Wagner and Foster, 2020). USA has also realised the benefits of AM on the improvement of the supply chain. The aircraft and automotive industry were the first to adopt additive manufacturing in the USA (Jiang, Kleer and Frank T. Piller, 2017a). General Electric (GE), Mercedes Benz and Disney have also adopted 3D printing technology in improving their supply chains by bringing manufacturing closer to the customer, cutting down transportation and logistics costs g (Arbabian, Wagner and Foster, 2020). AM has proven to be faster than subtractive for big batches because of the ability to have many parts in a single build. AM for complex parts is also cheaper than in traditional manufacturing. As the part complexity becomes simpler the traditional manufacturing becomes more economical. Studies in the USA are more focused on the energy consumption of AM compared to traditional manufacturing. Improving the supply chain is also important in the USA as a major world economy (Huang *et al.*, 2015).

2.2.2 Germany Perspective

Germany also focuses on energy consumption of AM when looking at sustainability (Yi *et al.*, 2020) (Hettesheimer, Hirzel and Roß, 2018b). Germany industry aims to reduce energy demand in any process it develops (Wirtz, Rehtanz and Wiederkehr, 2021). Germany also intends to use AM to establish sustainable business models. There are few studies that highlight the importance of business model and more need to be established and documented (Cardeal and Höse, 2020). Germany articles highlight the importance of evaluating the importance of sustainable business models in the lifecycle of AM. This includes the manufacturing of spare parts and lighter weight aircraft parts (Cardeal and Höse, 2020) (J Jakob Heinen and Hoberg, 2019). It was also highlighted that ware-housing reduces storage costs, thus improving the profitability of a business (Cardeal and Höse, 2020).

It is difficult to talk about one section of sustainability without including the other aspects. Economic sustainability also depends on environmental sustainability and social sustainability (Hettesheimer, Hirzel and Roß, 2018b). If a project proves to be economically sustainable but not environmentally friendly it can be shut down by local governments and environmentally conscious investors may choose not to invest. Social sustainability is also crucial because many of the customers may be affected by the business model directly or indirectly (Cardeal and Höse, 2020). The biggest challenge in AM is the potential to infringe on intellectual property rights (Jiang, Kleer and Frank T. Piller, 2017b). A solution to ensure organisations gain trust that AM's potential to infringe on intellectual property rights. With AM blueprints of parts can be transferred world-wide and easily be built using AM technologies around the world.

Process parameters are also areas that establish are focused on in economic sustainability studies. Process parameter that include laser power, particle size and particle size distribution are important in the efficient running of AM (Wirtz, Rehtanz and Wiederkehr, 2021). Running AM processes efficiently ensure that there is little waste and scrap. Energy savings are also a result of running AM efficiently. Mass customisation has also been a benefit of AM in Germany. Germany makes customised and highly complex parts which could be highly expensive for conventional manufacturing. AM is the technology of choice for highly customised products (Attaran, 2016).

The studies were also grouped in their area of focus to give an overview of which areas need focus for AM. In all the three countries the main area of focus in economic sustainability is energy consumptions (Hettesheimer, Hirzel and Roß, 2018b) (Yi *et al.*, 2020) (Wirtz, Rehtanz and Wiederkehr, 2021) (Pannitz and Sehrt, 2020) (Marcus A Jackson *et al.*, 2018) (Gutierrez-osorio, Ruiz-huerta and Caballero-ruiz, 2019) (Pontevedra *et al.*, 2019) (Arbabian, Wagner and Foster, 2020). Energy consumption is the area which most companies focus on in for AM sustainability.

2.2.3 South African Perspective

The economic benefits of AM in South Africa are clear and many organisations are carrying out studies to prove that AM is technically and economically viable.
Among these organisations are:

1. Council for Scientific and Industrial Research (CSIR)
2. Necsa
3. Aeroswift

Compared to Germany and America, South Africa has a lot of catching up to do though it is leading in Africa. More focus needs to be emphasised on the economic viability of AM and the activities that feed into AM. Germany has a high investment in AM in relation to its whole manufacturing economy. The USA has a high investment in AM, but compared to its economy it is still not highly invested in it (Nahirna, 2019).

The AM value stream comprises of the
1. Printing material making process
2. 3D printing
3. Reconditioning

The searches reflect a huge gap in the economic analyses of AM. Most studies are focused on the technical aspects of AM.

A search on economic sustainability of spheroidization of AM metals yielded no results for South Africa showing that the economic aspects of spheroidization are under researched at the moment. Spheroidization can positively impact AM activities by reconditioning powder that is no longer fit for use, thus reducing waste. This also improves the profitability of AM as a whole.

In Africa; South Africa, Morocco and Egypt are the leaders in adopting AM. Cameroon and Botswana are also following in adopting AM. Many countries in Africa are poor and investing in new technology that has little guarantee of growing the economy is difficult. Within the countries that have adopted AM, the economic sustainability must be proven economically, technically, socially and environmentally for the technology to be adopted in developing countries.

At the moment the major industries where AM is economically viable in South Africa and the rest of the world are

1. Medical sector
2. Aerospace industries
3. Custom automobiles
4. Spare parts of specialised machinery

Within the health sector, manufacturing of titanium inserts for replacements of bones in humans is now common (Attaran, 2016). These are specialised and unique products which are only economically viable if manufactured through AM. The health sector AM also allows for intricate designs which would be extremely expensive to make using conventional methods and sometimes impossible to make. In the South African; Council for Scientific and Industrial Research (CSIR), Collaborative Programme in Additive Manufacturing (CPAM), and Necsa are among the leading organisations that have played a big role in advancing the adaptation of the AM technology. Central University of Technology (CUT) has been conducting much of the research related to Ti6Al4V selective laser printing. In the medical industry in South Africa the technology has the potential to alter the way the medical industry functions economically, and technically.

2.3 Disruption of the supply chain

AM economic impacts are indirect. The potential to disrupt the supply chain is one of the ways AM impacts the economy (Emelogu et al., 2019) (Strong *et al.*, 2018). From the publications, the viability of AM also depends on the types of parts also made. Some of the criteria used make a decision if AM is viable are:

1. Production of Lightweight Parts
2. High Performance Critical Parts
3. Producing Spare Parts in Low Volume
4. Production Tools with Special Features

Criteria for selecting Parts for AM Application are:

1. Items to consider in economic sustainability
2. Geometric Complexity
3. Value of the Part
4. Production Volume
5. Lightweight Design
6. High Performance Material Change
7. Improved Efficiency
8. Reducing the Number of Components in an Assembly
9. Material Usage
10. Function of the Par
11. Time to Manufacture Component (Yi *et al.*, 2020)

AM can bring disruption to the supply chain. The disruption of the supply chain can alter economies and there is need to research more on the extent which the supply chain is affected by AM (Emelogu *et al.*, 2019).

2.4 Decentralisation by AM

Studies from the literature review also discuss decentralisation as a driver for economic sustainability of AM (Benner and Siemsen, 2017). AM can bring decentralisation to the manufacturing side. Decentralisation has a few economic benefits which are:

1. Decision making is spread among different managers cutting down on time wastage.
2. Manufacturing is bought closer to client and this is particularly important for the spare parts manufacturing.
3. Lead time to customer is short.

The different manufacturing plants increase the cost of investments and thus cannot be suited for mass production (Dircksen, Dircksen and Feldmann, 2020). Decentralisation is beneficial for low volume production and specialised parts. The decentralisation helps in making the manufacturing of spare parts easier and closer to the customer (Ghobadian *et al.*, 2020). The other advantage which most of the literature discusses is the disruption of the supply chain worldwide which also has economic implications. Some of the economic implications mean some processes are eliminated in the chain.

2.5 Spheroidization in South Africa as a Tool for Economic Growth for AM

The recondition of the printing material is all an effort to make the AM economically sustainable. In South Africa Necsa is currently the only plant that can recondition Ti6Al4V through spheroidization. Proving the economic sustainability is one of the steps that need to be taken at Necsa to increase their chances of being accepted in industry.

Spheroidization has the potential to be economically benefiting the South African AM sector. Among these benefits are the potential to:

1. reduce the need to extract more titanium ore,
2. cut down on procurement of titanium powder
3. reducing pollution which in turn reduces penalties from environmental bodies
4. Improve the quality of printed products.

Currently in South Africa little has been published on the economic sustainability of spheroidization of Ti6Al4V, but efforts are still ongoing to prove its sustainability. At the moment the economic sustainability of AM and spheroidization still needs to be proven in all territories. There are very few countries worldwide that have adopted AM as of 2021. The countries that have not adopted AM need proof that the high capital investment of AM is worth the investment.

Currently at Necsa there has been some progress with spheroidization. With reference to CSIR there has not been powder that has been used for commercial purposes. The current challenge is attaining the flowability require for the powder to be printed. To determine the economic sustainability of spheroidization in South Africa there is need to first ensure that the powder meets the requirements for SLM.

2.5.1 Aerospace Industry

Metal AM has seen significant growth in aerospace and there is need to ensure more research is done to make the AM process more economically viable. Reducing the cost of AM through recycling its material also ensures that it is economically viable (Blakey-Milner *et al.*, 2021). In the aerospace industry there is a requirement for light weight parts. Light weight parts in an aircraft ensure less fuel consumption which also translates to less overhead expenses in the long run (Pannitz and Sehrt, 2020). AM allows complex designs and also reduce assembly time as parts can be merged in AM (Yi *et al.*, 2020). Air craft parts made with subtractive manufacturing waste 90% of the material while in AM the material is reusable for multiple cycles (Huang *et al.*, 2015). This ability to reuse material makes the AM process economic and sustainable (Daraban *et al.*, 2019). AM gives aerospace engineers freedom of design (Yi *et al.*, 2020) (Yang *et al.*, 2020) (Liu *et al.*, 2018). This can ensure that the designers make more efficient parts which could not be produced by conventional manufacturing methods.

2.5.2 Medical Industry

In the Medical industry customisation is common especially in the manufacturing of prosthetics. AM has proven to be highly economical in the making of customised prosthetics (Marro, Bandukwala and Mak, 2016). South Africa is driving towards adopting AM in the medical industry (Yadroitsev *et al.*, 2018). To date many prosthetics have been made that have been fitted in humans (Günther *et al.*, 2017) (Attaran, 2016). Adaptation of AM in the medical industry is fairly fast as there is need to have AM equipment close to the customer. AM has a shorter lead time if there is need to make medical prosthetics quicker that in traditional manufacturing. Some human prosthetics would take much longer to make using traditional manufacturing and would also be more expensive due to the tool change over. If prosthetics are made using subtractive manufacturing material waste would typically be at 90% (Childerhouse and Jackson, 2019). In many cases some geometries that AM can achieve are impossible to achieve with subtractive or would be highly expensive to achieve (Liu *et al.*, 2018). If the prosthetics are manufacturing with mould the process would be highly expensive as the mould would be discarded as no two humans are exactly the same.

2.5.3 Choosing the right technology for manufacturing

In choosing the technology there are factors to be chosen to determine the appropriate technology. These include volume, complexity of the product, size of the product cost and delicacy (Liu and Shin, 2019) (Marro, Bandukwala and Mak, 2016). On the economic sustainability of the technology, productivity, quality cost, delay time, innovation and profitability are to be researched before choosing technology is best. The AM technology eliminates wastes as most of the material goes into the printed product with little material going into making support structures. AM is the technology of choice if parts are complex and highly customised (Marro, Bandukwala and Mak, 2016). With the ability to print lighter parts than in conventional manufacturing the savings that AM bring are more long term in curtain industries like aerospace and automotive industries. The low delivery time associated with AM reduces opportunity costs associated with high delivery time. AM also has the potential to improve the energy efficiency (Gao, Wolff and Wang, 2021a).

The quality cost in AM is lower as there is less tooling associated with improving tolerance (Yang *et al.*, 2020) (Huang *et al.*, 2015). AM requires little post processing, thus can be economically sustainable in cases where low tolerances are required. In AM innovation is made easier as the product development stage of product is shorter. In the areas where AM is profitable, there is still need to improve the process chain. This is where the spheroidization of used powder comes in which is a recycling process. As mentioned earlier Necsa is the only plant in South Africa that spheroidizes metals and the research is still on going to improve the process.

Spheroidization can improve the profitability of AM by:

1. Reducing wasted material through recycling
2. Improving the quality of the material used in additive material (Qin *et al.*, 2019)

Spheroidization improves some properties of metal powder which are:
1. Flowability
2. Chemical composition
3. Density
4. Morphology
5. Powder shape (Murray *et al.*, 2019b)

Improving the quality of the powder ensures the printing process takes places smoothly with less defects caused by inconsistent powder (Santecchia *et al.*, 2019). Reducing waste in manufacturing is also financially beneficial to an organisation as it can reduce material and energy costs (Watson and Taminger, 2018).

3 Discussion

There are few studies highlighting the economic sustainability of spheroidization and AM. The literature revealed that the studies that are available relation to economic sustainability. From the search, decentralisation is one of the main advantages of AM. The economic sustainability is also evident as parts get more complex. The medical industry and the aerospace industry benefit from AM as they require complex parts. In organisations where customisation of products is a major activity, AM is the technology of choice (Yang and Li, 2018). Within the value stream of AM, spheroidization can make AM more economical. Figure 2 shows the value chain of AM and the flow activities. In economic viability and sustainability studies, all aspects of the AM value stream must be looked into in depth. The extraction of metals for AM affect the profitability. Spheroidization can be added in the AM value stream to improve the economic sustainability of AM. The spheroidization process can reduce the need to extract more metals by recycling the AM material (Gao, Wolff and Wang, 2021b). This also brings about cost saving for AM. More studies are needed in the powder processing steps especially when it pertains to economics of AM. Necsa focuses more on the spheroidization side of AM and more economic sustainability studies should be conducted for spheroidization.

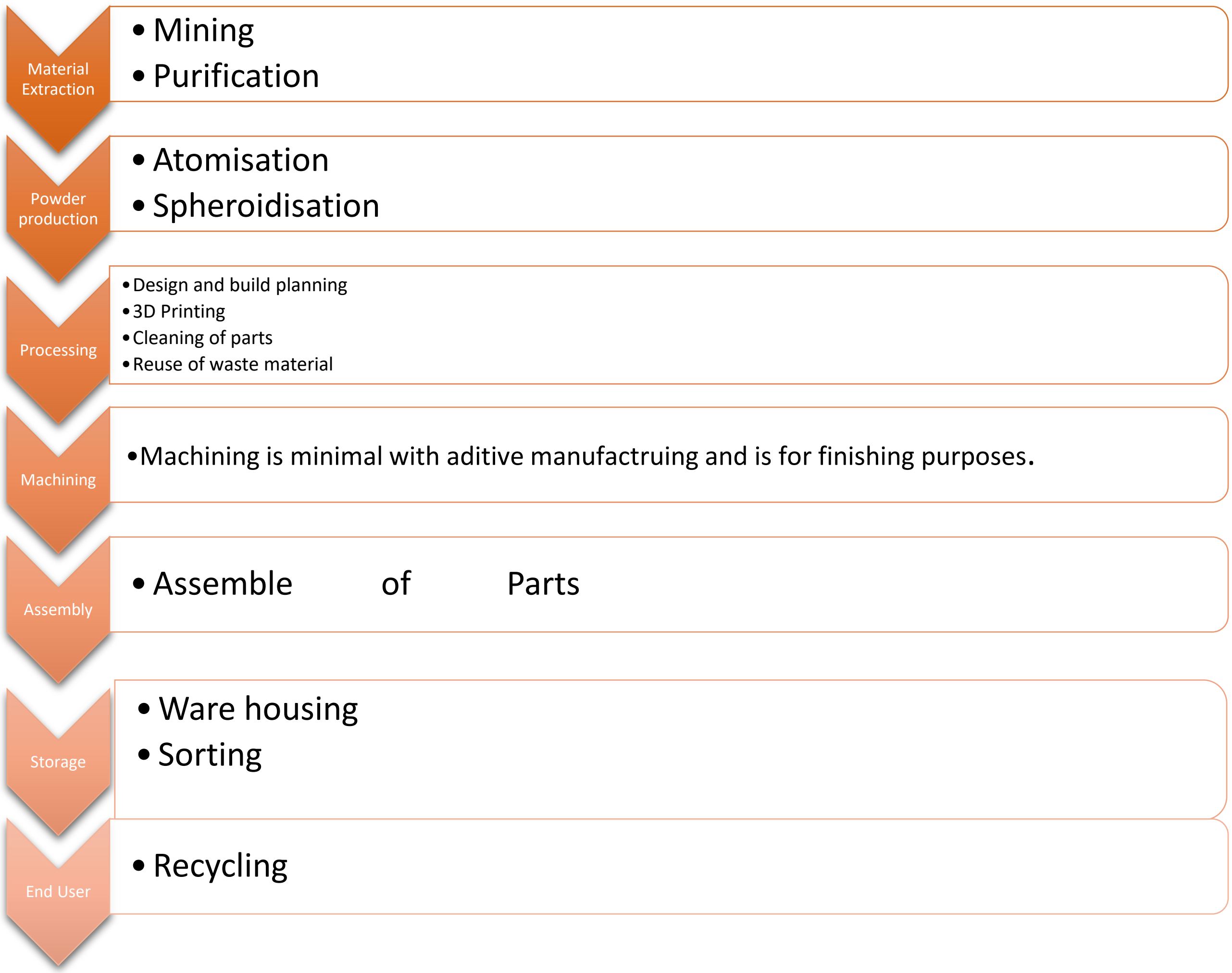

Figure 2: Life cycle for additive manufacturing

Within the metal powder value stream spheroidization can ensure that rejected powder is not disposed by reconditioning. Spheroidization can improve the AM process by ensuring unused powder is reused.

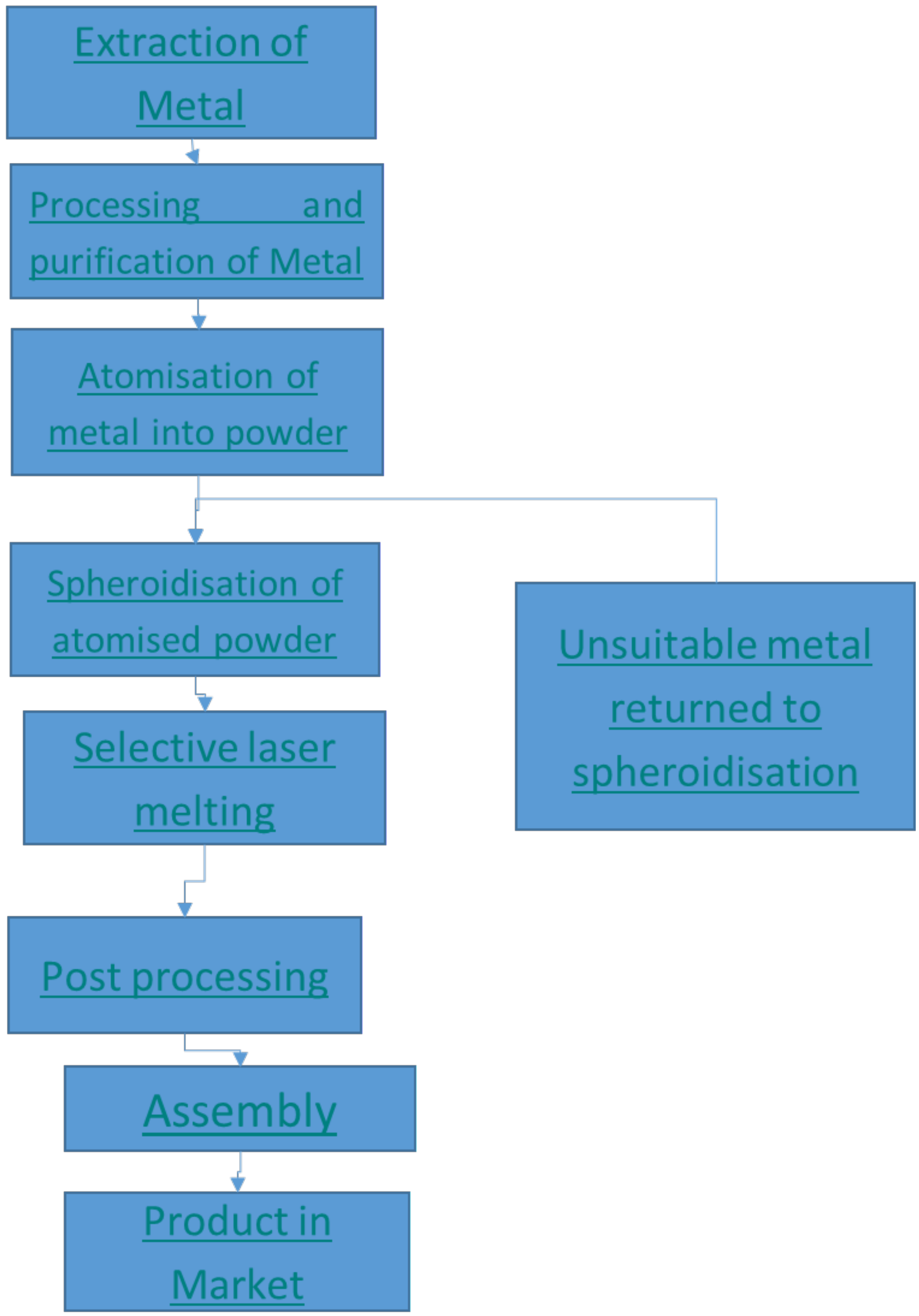

Figure 3: AM value chain with spheroidization Added

From Figure 3 the spheroidization process is show to be cyclic. This means that powders that is left unsintered can be reused multiple times thus saving on material cost.

4 Conclusion

AM is economically sustainable though it still needs improvements. The economic sustainability of AM still needs to be proven. The literature revealed that for AM to be accepted in industry, there is need to improve and prove the economic sustainability. More studies need to be conducted with regards to the economic sustainability of AM. Focus also needs to be placed on the other aspects of AM that add to the value chain of manufacturing. These aspects include atomisation and manufacturing of feed stock for AM, spheroidization (reconditioning of metals) and the products utilisation stage of AM.

5 Acknowledgements

The authors would like to acknowledge the Department of Science and Innovation (DSI), through the Advanced Materials Initiative (AMI), for the financial support in conducting this study.

6 References

Arbabian, M.E., Wagner, M.R. and Foster, M.G. (2020) "The impact of 3D printing on manufacturer – retailer supply chains," *European Journal of Operational Research*, 285(2), pp. 538–552. doi:10.1016/j.ejor.2020.01.063.

Attaran, M. (2016) "3D Printing : Enabling a New Era of Opportunities and Challenges for Manufacturing 3D Printing : Enabling a New Era of Opportunities and Challenges for Manufacturing," 4(October), pp. 30–38.

Bao, Q. *et al.* (2021) "The preparation of spherical metal powders using the high-temperature remelting spheroidization technology," *Materials and Design*, 199(30), p. 109382. doi:10.1016/j.matdes.2020.109382.

Ben-ner, A. and Siemsen, E. (2017) "Decentralization and Localization of Production : The Organizational and Economic Consequences of Additive Manufacturing (3D Printing)," (March). doi:10.1177/0008125617695284.

Blakey-Milner, B. *et al.* (2021) "Metal additive manufacturing in aerospace: A review," *Materials and Design*, 209. doi:10.1016/j.matdes.2021.110008.

Cardeal, G. and Höse, K. (2020) "Sustainable Business Models – Canvas for Sustainability , Evaluation Method , and Their Application to Additive Manufacturing in Aircraft Maintenance," pp. 403–404.

Childerhouse, T. and Jackson, M. (2019) "Near Net Shape Manufacture of Titanium Alloy Components from Powder and Wire : A Review of State-of-the-Art Process Routes." doi:10.3390/met9060689.

Crocetti, E. (2016) "Systematic Reviews With Meta-Analysis: Why, When, and How?," *Emerging Adulthood*, 4(1), pp. 3–18. doi:10.1177/2167696815617076.

Daraban, A.E.O. *et al.* (2019) "A Deep Look at Metal Additive Manufacturing Recycling and Use Tools for Sustainability Performance," *Sustainability* [Preprint].

Dircksen, M., Dircksen, M. and Feldmann, C. (2020) "Holistic evaluation impacts of additive manufacturing on and in global supply chains," *Transportation Research Procedia*, 48(2019), pp. 2140–2165. doi:10.1016/j.trpro.2020.08.272.

Emelogu, A. *et al.* (2019) "Distributed or centralized? A novel supply chain configuration of additively manufactured biomedical implants for southeastern US States," *CIRP Journal of Manufacturing Science and Technology*, 24, pp. 17–34. doi:10.1016/j.cirpj.2018.12.001.

Gao, C., Wolff, S. and Wang, S. (2021a) "Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis," *Journal of Manufacturing Systems*. Elsevier B.V., pp. 459–472. doi:10.1016/j.jmsy.2021.06.011.

Gao, C., Wolff, S. and Wang, S. (2021b) "Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis," *Journal of Manufacturing Systems*. Elsevier B.V., pp. 459–472. doi:10.1016/j.jmsy.2021.06.011.

Ghobadian, A. *et al.* (2020) "Examining legitimatisation of additive manufacturing in the interplay between innovation, lean manufacturing and sustainability," *International Journal of Production Economics*, 219(1), pp. 457–468. doi:10.1016/j.ijpe.2018.06.001.

Giffi, G.A., Gangula, B. and Illinda, P. (2014) "3D opportunity in the automotive industry," *A Deloitte series on additive manufacturing* [Preprint].

Godina, R. *et al.* (2020) "Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context," *Sustainability (Switzerland)*, 12(17), pp. 1–21. doi:10.3390/su12177066.

Günther, J. *et al.* (2017) "Fatigue life of additively manufactured Ti–6Al–4V in the very high cycle fatigue regime," *International Journal of Fatigue*, 94, pp. 236–245. doi:10.1016/j.ijfatigue.2016.05.018.

Gutierrez-Osorio, A.H. *et al.* (2019) "Energy consumption analysis for additive manufacturing processes," *International Journal of Advanced Manufacturing Technology*, 105(1–4), pp. 1735–1743. doi:10.1007/s00170-019-04409-3.

Gutierrez-osorio, A.H., Ruiz-huerta, L. and Caballero-ruiz, A. (2019) "Energy consumption analysis for additive manufacturing processes," *The International Journal of Advanced Manufacturing Technology*, The Intern(105), pp. 1735–1743.

Heinen, J. Jakob and Hoberg, K. (2019) "Assessing the potential of additive manufacturing for the provision of spare parts," *Journal of Operations Management*, 65(8), pp. 810–826. doi:10.1002/joom.1054.

Heinen, J Jakob and Hoberg, K. (2019) “Assessing the potential of additive manufacturing for the provision of spare parts,” (July), pp. 810–826. doi:10.1002/joom.1054.

Hettesheimer, T., Hirzel, S. and Roß, H.B. (2018a) “Energy savings through additive manufacturing: an analysis of selective laser sintering for automotive and aircraft components,” *Energy Efficiency*, 11(5), pp. 1227–1245. doi:10.1007/s12053-018-9620-1.

Hettesheimer, T., Hirzel, S. and Roß, H.B. (2018b) “Energy savings through additive manufacturing : an analysis of selective laser sintering for automotive and aircraft components,” pp. 1227–1245.

Huang, Y. *et al.* (2015) “Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations,” *Journal of Manufacturing Science and Engineering*, 137(1), p. 014001. doi:10.1115/1.4028725.

Jackson, Marcus A. *et al.* (2018) “Energy Consumption Model for Additive-Subtractive Manufacturing Processes with Case Study,” *International Journal of Precision Engineering and Manufacturing - Green Technology*, 5(4), pp. 459–466. doi:10.1007/s40684-018-0049-y.

Jackson, Marcus A *et al.* (2018) “Energy Consumption Model for Additive-Subtractive Manufacturing Processes with Case Study,” 5(4), pp. 459–466. doi:10.1007/s40684-018-0049-y.

Jiang, Q. *et al.* (2019) “Emergy-based life-cycle assessment (Em-LCA) for sustainability assessment: a case study of laser additive manufacturing versus CNC machining,” *International Journal of Advanced Manufacturing Technology*, 102(9–12), pp. 4109–4120. doi:10.1007/s00170-019-03486-8.

Jiang, R., Kleer, R. and Piller, Frank T. (2017a) “Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030,” *Technological Forecasting and Social Change*, 117, pp. 84–97. doi:10.1016/j.techfore.2017.01.006.

Jiang, R., Kleer, R. and Piller, Frank T. (2017b) “Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030,” *Technological Forecasting and Social Change*, 117, pp. 84–97. doi:10.1016/j.techfore.2017.01.006.

Jiang, R., Kleer, R. and Piller, Frank T (2017) “Technological Forecasting & Social Change Predicting the future of additive manufacturing : A Delphi study on economic and societal implications of 3D printing for 2030,” *Technological Forecasting & Social Change*, 117, pp. 84–97. doi:10.1016/j.techfore.2017.01.006.

Liu, S. and Shin, Y.C. (2019) “Additive manufacturing of Ti6Al4V alloy : A review,” *Materials & Design*, 164, p. 107552. doi:10.1016/j.matdes.2018.107552.

Liu, Z.Y. *et al.* (2018) “Energy Consumption in Additive Manufacturing of Metal Parts,” 26, pp. 834–845. doi:10.1016/j.promfg.2018.07.104.

Ma, J. *et al.* (2018) “An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment,” *Journal of Cleaner Production*, 192, pp. 55–70. doi:10.1016/j.jclepro.2018.04.249.

Marro, A., Bandukwala, T. and Mak, W. (2016) “Three-Dimensional Printing and Medical Imaging: A Review of the Methods and Applications,” *Current Problems in Diagnostic Radiology*, 45(1), pp. 2–9. doi:10.1067/j.cpradiol.2015.07.009.

Murray, J.W. *et al.* (2019a) “Spheroidisation of metal powder by pulsed electron beam irradiation,” *Powder Technology*, 350, pp. 100–106. doi:10.1016/j.powtec.2019.03.041.

Murray, J.W. *et al.* (2019b) “Spheroidisation of metal powder by pulsed electron beam irradiation,” *Powder Technology*, 350, pp. 100–106. doi:10.1016/j.powtec.2019.03.041.

Nagarajan, H.P.N., Raman, A.S. and Haapala, K.R. (2018) “A Sustainability Assessment Framework for Dynamic Cloud-based Distributed Manufacturing,” in *Procedia CIRP*. Elsevier B.V., pp. 136–141. doi:10.1016/j.procir.2017.11.120.

Nahirna, M. (2019) “Additive Manufacturing Around the World_ What is the State of 3D Printing Adoption in North America and Europe_ - AMFG.”

Oyessola, M. *et al.* (2018) “Sustainability of Additive Manufacturing for the South African aerospace Sustainability of Additive Manufacturing for the South African aerospace industry: A business model for laser technology production, 28th CIRP Design Conference, May 2018, Nantes, Fr,” *Procedia CIRP*, 72, pp. 1530–1535. doi:10.1016/j.procir.2018.03.072.

Pannitz, O. and Sehrt, J.T. (2020) “Transferability of Process Parameters in Laser Powder Bed Fusion Processes for an Energy and Cost E ffi cient Manufacturing.”

Pontevedra, V. *et al.* (2019) “Integrated traditional traditional and and additive additive manufacturing manufacturing production production profitability profitability model Costing models for capacity optimization between used and,” *Procedia Manufacturing*, 34, pp. 619–630. doi:10.1016/j.promfg.2019.06.121.

Qin, Q. *et al.* (2019) “Spheroidization of tantalum powder by radio frequency inductively coupled plasma processing,” *Advanced Powder Technology*, 30(8), pp. 1709–1714. doi:10.1016/j.apt.2019.05.022.

Santecchia, E. *et al.* (2019) “Cross-Contamination Quantification in Powders for Additive Manufacturing : A Study on Ti-6Al-4V and.”
Strong, D. *et al.* (2018) “Hybrid manufacturing – integrating traditional manufacturers with additive manufacturing (AM) supply chain,” *Additive Manufacturing*, 21, pp. 159–173. doi:10.1016/j.addma.2018.03.010.
Trentin, M., Adamczuk, G. and Batistus, D.R. (2015) “A systematic approach for the analysis of the economic viability of investment projects A systematic approach for the analysis of the economic viability of investment projects José Donizetti de Lima * Marcelo Gonçalves Trentin Dayse Regina Batistus Dalmarino Setti,” (August). doi:10.1504/IJEME.2015.069887.
Watson, J.K. and Taminger, K.M.B. (2018) “A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption,” *Journal of Cleaner Production*, 176, pp. 1316–1322. doi:10.1016/j.jclepro.2015.12.009.
Wirtz, A., Rehtanz, C. and Wiederkehr, P. (2021) “Investigation of electrical power consumption of an additive process chain Investigation of electrical power consumption of an additive process chain 28th CIRP Design Conference, May 2018, Nantes, France A new methodology to analyze the functional and phy,” in *14th CIRP Conference on Intelligent Computation in Manufacturing Engineering*. Elsevier B.V., pp. 358–363. doi:10.1016/j.procir.2021.03.103.
Yadroitsev, I. *et al.* (2018) “Qualification of Ti6Al4V ELI Alloy Produced by Laser Powder Bed Fusion for Biomedical Applications,” *Jom*, 70(3), pp. 372–377. doi:10.1007/s11837-017-2655-5.
Yang, H. *et al.* (2020) “Six-Sigma Quality Management of Additive Manufacturing Six-sigma Quality Management of Additive Manufacturing,” (October). doi:10.1109/JPROC.2020.3034519.
Yang, Y. and Li, L. (2018) “Cost modeling and analysis for Mask Image Projection Stereolithography additive manufacturing: Simultaneous production with mixed geometries,” *International Journal of Production Economics*, 206, pp. 146–158. doi:10.1016/j.ijpe.2018.09.023.
Yi, L. *et al.* (2020) “An eco-design for additive manufacturing framework based on energy performance assessment,” 33(January). doi:10.1016/j.addma.2020.101120.

Biographies

André van der Merwe holds a Bachelors of Mechanical Engineering, a Masters of Industrial Engineering and a PhD Engineering on the topic of “Air suspension to reduce Human exposure to Vibration”. He worked 18 years in industry as engineering manager in Africa and Europe. His subsequent 16-year academic career produced several conference and journal publications. He is a reviewer for several national and international peer-reviewed publications and conferences. He is often frustrated by academic thinking and seeks real world application for every research project he endeavors. He is currently at Stellenbosch University at the Industrial Engineering department in the field of Resource Efficiency Engineering Management. REEM research group focuses on Commercial Readiness Indicators for Industry 4.0, which includes Additive Manufacturing, Human-Machine interface and Food Security using Internet of Things. He is the current vise-chairman for RAPDASA, with a focus on skills development of technicians for the industry. For sport and leisure, he is competitive in road cycling, mountain biking enjoys gardening, scuba diving, skiing, intensive olive farming, home automation and aquaponics.

Stephen Matope is an Associate Professor in the Department of Industrial Engineering, Stellenbosch University with over 16 years of lecturing industrial engineering related subjects at university level. His research interests are in advanced manufacturing covering additive manufacturing, manufacturing processes and manufacturing systems.

Tsepo Dube is an industrial engineering student studying a PhD at Stellenbosch University. Studied his first degree in industrial and manufacturing engineering at the National university of science and technology in Zimbabwe where also completed his master in industrial engineering. His research interests are in advanced materials and additive manufacturing.

Hertzog Bissett joined Necsa (The South African Nuclear Energy Corporation) at the start of 2009 working in the Plasma Technology group obtaining knowledge in the use and operation of various plasma systems (“hot” and “cold” plasmas) and high temperature systems such as inductive coupling heating. Hertzog was also part of the Uranium Chemistry group at Necsa looking at various methods of uranium dissolution, extraction and purification. In 2012 Dr. Bissett obtained his Ph.D. degree also from the North-west University for the study “Membrane based separation of nitrogen, tetrafluoromethane and hexafluoropropylene”. Currently, Dr. Bissett is part of the Nuclear Materials group within Applied Chemistry at Necsa working on various projects include the AMI-Nuclear Materials Development Network especially relating to spheroidiszation.