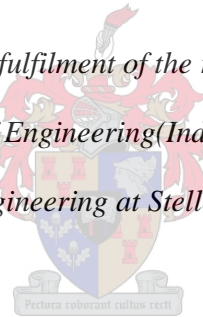


Developing a Framework to Investigate the Resource Efficiency of Manufactured Titanium Components Process Chains

by

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*Thesis presented in fulfilment of the requirements for the
degree of Master of Engineering (Industrial Engineering)
in the faculty of Engineering at Stellenbosch University.*



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***Declaration***

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Opsomming

As deel van 'n steeds groeiende tendens in beide die lug en mediese bedryf, het vereistes gestyg wat die gebruikers en vervaardigers dryf om Titaan komponente, met komplekse geometrieë en vermoë wat in die verlede net van gedroom was, te ontwikkel. 'n Oplossing wat dit moontlik gemaak het vir Titaan-komponent vervaardigers regoor die wêreld het gekom in die vorm van beide Toevoegings- (TV) en Subtraktiewe-Vervaardiging (SV).

Deur te streef na meer volhoubare proses kettings, moet vervaardigers voortdurend poog om die hulpbron doeltreffendheid van hul vervaardigingsprosesse te verbeter. As deel van hierdie, het toevoeging en subtraktiewe vervaardiging tegnologie al hoe belangriker vir die vermindering van afval, tyd en koste geword. Verskeie inset faktore beïnvloed die effektiwiteit van 'n toevoegende benadering en het dus ook 'n impak op volhoubaarheid. Hierdie proefskrif ondersoek die faktore en eienskappe wat die hulpbron doeltreffendheid van toevoegings- en subtraktiewe-vervaardigingsproses kettings beïnvloed, tot die samestelling van 'n evaluerings raamwerk en 'n Excel-gebaseerde instrument. Die ontwerp en ontwikkeling van verskillende TV en SV vervaardiging strategieë, vir die vervaardiging van hierdie dele, sal, deur middel van 'n ontwikkelde raamwerk model, toelaat vir 'n in-diepte evaluering en vergelyking van watter proses ketting die mees hulpbron doeltreffendste is. Die vermoë profiel van elke proses ketting kan beskryf word deur die volgende eienskappe te kwantifiseer:

- Vervaardigings Tyd
- Geometriese Akkuraatheid
- Vervaardigings Koste
- Energie Verbruik
- Afval Materiaal

'n Oorsig word op die verskillende benaderings en tegnieke wat gebruik is word gegee met die doel om die identifisering van die mees invloedryke faktore te vergemaklik. Die raamwerk is gevalideer met behulp van Titaan lugvaart en biomediese maatstaf komponente sowel as vraelyste. Die Excel-gebaseerde instrument is ook gevalideer deur die maatstaf komponente en het daardeur, in wese, die vermoë om die proses beplanners te help met besluite oor Titaan vervaardigingsproses ketting seleksie bewys. In die algemeen poog hierdie studie om akademiese waarde by te dra en ter selfde tyd met bedryf vennote en moontlike TV en SV vervaardigers te help. Riglyne sal ook gegee word vir die moontlike eindgebruikers oor hoe hulle te werk moet gaan om hulpbronne doeltreffend te gebruik.



Abstract

As part of an ever growing trend regarding both the aerospace and medical industry, requirements have risen that allow the users and manufacturers the ability to develop Titanium components with complex geometries, which in the past were only dreamed of. A solution that has made this possible for Ti-component manufacturers all over the world has come in the form of both additive and subtractive manufacturing.

Pursuing more sustainable process chains, manufacturers are constantly striving to enhance the resource efficiency of their manufacturing systems. As part of this, additive and subtractive manufacturing technologies have become increasingly important for reducing waste, time and costs. Various input factors affect the efficiency of an additive approach and therefore also have an impact on the sustainability. Towards the establishment of an evaluation framework and an Excel based tool, this work investigates all the factors and characteristics that influence the resource efficiency of additive and subtractive manufacturing process chains. The design and development of various AM and SM manufacturing strategies for the fabrication of these parts will allow for an in-depth evaluation and comparison of which process chain is the most resource efficient through the steps of a developed framework model. The capability profile of each process chain can be outlined by quantifying the characteristics that follow:

- Manufacturing Time
- Geometrical Accuracy
- Manufacturing Cost
- Energy Consumption
- Material Waste

An overview is provided on the different approaches and techniques that have been used with the aim of identifying the most influential factors. The framework was validated using titanium aerospace and biomedical benchmark components together with conducted surveys. The Excel based tool was validated through the benchmark components, thereby essentially proving its ability to assist the process planners with decisions regarding Titanium manufacturing process chain selection.

This study strives to contribute its value academically, together with industry partners and possible AM and SM manufacturers. Guidelines will also be given for the possible end users on how they should go about being more resource efficient.



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Terms of Reference

Bio - compatible	The ability of a certain material to perform well under the host characteristics and not evoke a response [1]
Conceptual Framework	An initial linkage of concepts through a network [2]
Hybrid Process	A combination of different manufacturing technologies to form one process, for example, combining CNC machining and SLM
Iteration	The repetition of a process in order to approach a desired goal [3]
Manufacturing Process	Steps in which a raw material is developed into the required final product [4]
Osseo-integration	Bond between the bone of the host and the bio-compatible material [5]
Process	A series of steps taken for the completion of a specific end [6]
Process Chain	A sequence of processes that have been arranged to take place in order for the output of a product or service [7]
Resource Efficiency	Optimising a process to limit cost, time, waste and energy consumption of a process [8]
Sustainable Manufacturing	Developing components/products through resource efficiency processes, minimising environmental impacts together with energy conservation [9]
Value Stream	Process of designing, developing and providing a service or product to the market [10]



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Glossary

3D	Three Dimensional
6R	Reduce, redesign, remanufacture, recycle, reuse, recover
Al	Aluminium
AM	Additive Manufacturing
C	Carbon
CAD	Computer Aided Design
CADD	Computer Aided Design and Drafting
CAM	Computer Aided Manufacturing
CEA	Constant Engagement Angle
cm	Centimetres
CMM	Co-ordinate Measuring Machine
CNC	Computer Numerical Control
CSIR	Council for Scientific and Industrial Research
DMADV	Define, Measure, Analyse, Design, Verify
DMAIC	Define, Measure, Analyse, Improve, Control
EBM	Electron Beam Melting
Fe	Iron
GOM	Geometrical Optical Measuring
H	Hydrogen
kW	Kilowatt
kg	kilogram
mg	milligram
min	minutes



N	Nitrogen
O	Oxygen
PDCA	Plan-Do-Check-Act
PM	Process Manufacturing
PLC	Product Life Cycle
R&D	Research and Development
SA	South Africa
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
STL	Stereolithography
Ti	Titanium
TiCoC	Titanium Centre of Competence
V	Vanadium
VBA	Visual Basic for Applications
Vol	Volume



1. Introduction

1.1 Background

Over the past few years, Titanium as a raw material has had a significant impact on both the aerospace and medical industries. Regarding the aerospace industry, aircraft manufacturers have stated that there will be an increase in cargo and passenger aircrafts from 18 640 to 37 463 between the years 2013 and 2033 [11]. Due to the fact that energy consumption within these aircrafts is extremely high while in operation, components within the aircraft were required to be manufactured innovatively so as to reduce the weight of the aircraft. The components designed are required to be within the range of civil aviation together with being energy conscious. In order to accept this feat, the new titanium components needed to have their thickness minimised together with their rigidity maximised. This understandably had an effect on the manufacturing front. A cost intensive, non-resource efficient process chain has to take place in which the components are developed by hammer forging products that were semi-finished. This thus leads to a high removal rates together with large demands on the milling process [12] [13].

Regarding the medical industry in the modern era, hip replacement design with a Titanium alloy has had a major development in the biomechanical research. The hip of a human is a synovial ball and socket joint and serves as the connector between the trunk of a human and the lower limbs [14]. Keeping this mind, the joint is often exposed to a number various weights and stress due to running/jumping etc. and these heavy loadings endanger the joint in the latter age of a human. The joint supports close to two thirds of a person's body weight when static [15]. This figure increases exponentially when performing activities such as running, jumping or climbing, under which the hip joint withstands forces up to 5 times the person's body weight. Frequent use of the hip joint under these conditions causes a steady degradation of the cartilage that supports the joint. This degradation often causes osteoarthritis (OA) which is currently the most frequent reason in which people require hip replacements [15] [16].

Following the above information, the need arises for manufacturing processes to produce components with highly complex geometries in less time as the demand for the parts increase. Concepts involving sustainable development have resulted in the efficiency improvement of these titanium manufacturing processes in order to reduce the waste consumption. These efficiency concerns have resulted in a shifting in focus to the process chains of manufacturing titanium components. An obvious way in improving the efficiency of the process chain will be to, as mentioned above, de-materialise the entire process which, in broad terms, refers to reducing the amount of materials and energy needed in the process. By evaluating the material consumption in the process, one will be able to close the material loops thus complementing the dematerialisation process [13].



When manufacturing these specific intelligent implants or aerospace components for example, there are a number of different ways in which one can go about achieving his/her need through various manufacturing methods. These different ways in which one can follow to achieve a given output is known as a process chain. As these processes within the process chain evolve with time, the aerospace parts together with medical parts will be able to optimised accordingly with regards to the manufacturing capability. Resource efficient process chains therefore evolve as an all-round manufacturing necessity due to the increasing resource costs. There are a number of different process chains in which the design and manufacture of both medical and aerospace components can be bought about, however through testing and evaluation of the different process chains one process chain should be more efficient than the other, leading to the purpose of this research.

1.2 Problem Statement

In both the aerospace and the medical industry, titanium components are composed of primary material ingots. The first step in titanium component production is the production of Titanium Sponge. Following this, processes including forging, melting and milling occur in order to create the Titanium component desired. The milling process creates increased chip removal rates with up to 95% [17]. There is too a high demand in energy for production of the titanium sponge which accounts of up to 85% of the total energy consumption in the process chain. That being said, it leads to possible optimisation techniques with regards to the energy aspects of the process chain as well as the ecological and efficiency aspects. By simply recycling the chips for the production of the ingot, the ecological aspect of the process chain can be improved. These two elements of resource efficiency are however not the only ones requiring attention. That being said, there are various process chains in which titanium components for both the aerospace and medical industry can be developed. And within these process chains a number of different variables can be altered in order to achieve an ‘optimal’ process chain and a resource conscious production cycle.

Manufacturing Industries in South Africa seem to also depend highly on knowledge and experience learned from past operation processes, thus creating small gaps in the general knowledge and general development of manufacturing technologies, resulting in potential process optimisation being limited. Following this, the need arises for external channels to create and possibly implement new technologies. These external channels are often universities or technology institutions.

The Manufacturing Industries of these Titanium components are also under constant pressure when trying to compensate for ever increasing costs. For the past 10 years, industries have solely focused on optimisation of specific processes in the manufacturing process chain, for example, optimising cutting operations with the aim of reducing resource usage. However, recently, the focus has shifted to improve the resource efficiency of



manufacturing processes by utilising different strategies, for example, the near-net-shaped technology which is directed towards reducing manufacturing times, material waste and costs while simultaneously improving productivity.

Currently in South Africa, there is no framework or tool that can be used in order to support manufacturers in choosing the 'correct' or most sustainable way to manufacture their components. This thus leaves a large window open for the development of a framework model for manufacturers to incorporate into their manufacturing planning with the aim of guiding them to the most resource efficient manufacturing process.

Development of a series of process chains together with the evaluation of the process chains is to be performed using the developed framework and excel based tool in order to investigate the most resource efficient process chain.

1.3 Research Objectives

The purpose of this study is to investigate the resource efficiency of process chains regarding titanium components. This should be accomplished by designing a framework in order to evaluate manufacturing process chains for components utilised both in the medical and aerospace industry. In order to achieve this study a series of objectives will need to be completed, namely:

- Identifying the key elements to be evaluated in the process chains (e.g. Manufacturing Time, Waste, Cost, Energy, Quality)
- Understanding the cause-effect relationship of the various factors effecting resource efficiency on the through production (For example, if the time increases, what effect will it have on the other outcomes)
- Develop steps or a framework in order to evaluate the resource efficiency of the process chains
- Identify the benchmark components to be evaluated
- Validate and iterate the framework with the identified benchmark components
- Conduct framework validation surveys through manufacturing specialists
- Develop an excel based tool supported by the developed framework in order to support the process planning of manufacturing
- Apply the data from the process chains of the benchmark components to the framework steps
- Determine the most resource efficient process chains for the manufactured titanium components

Once these objectives are complete, the framework together with the excel tool will be complete for future, possible industrial use.



1.4 Expected Contributions

The objective of this study is to develop a framework and excel tool to evaluate the resource efficiency of different process chains for titanium components. By conducting this particular study it will allow the industry developers of titanium components to potentially improve their design, reduce their cost, improve their system integration and accuracy and decrease their possible lead times of the components where necessary.

1.5 Proposed Study Approach and Methodology

The main objective of this study is to develop a framework and model to investigate the most resource efficient process chain in the manufacturing of intelligent medical implants and aerospace components. The research study was distributed between four phases which were namely the research analysis, framework development to an initial, conceptual framework, refinement of the framework through validation iterations and then conversion of the framework into an excel practical tool. The way in which these phases were conducted will be obtained by performing the steps below:

- Understand the way in which the intelligent implants and aerospace components can be successfully manufactured through an in depth literature study.
- Investigate the various manufacturing technologies one can use in the development of the of these components
- Consider different factors and characteristics that will be used in the analysis of the most resource efficient implant
- Investigate the operation procedures of the additive and subtractive machining through research journals and publications as this will form a large segment of the study
- Quantify any other criteria that could be involved with any experimental procedures
- Evaluate the different process chains in terms of the different aspects needed to compare the different processes with one another
- Develop process chains to be analysed in the manufacturing of Titanium components
- Investigate three benchmark components using a conceptually developed framework form literature, for the resource efficiency of their respective process chains
- Refine and Validate the framework with the benchmark components for an industrial environment



- Using the developed frameworks, examine the process chains after the manufacturing of the components. Inspect aspects such as the user-friendliness of the system, the accuracy, the speed of the process, the work volume and the economical values of the process
- Determine the most resource efficient process chain for the manufacturing of the three identified benchmark components
- Perform a quantitative analysis of the framework for the various benchmark components
- Conduct a survey to qualified, knowledgeable, manufacturing personnel in order to find shortcomings of the proposed developed frameworks and how the frameworks could be used for each manufacturing process chain
- Develop excel model from the framework to analyse the different process chains
- Compile data and conclude with the most resource efficient process chains for the respective components together with a suitable framework and excel tool that can be used by titanium manufacturers

Upon completion of the listed steps, the main objective of this research study will be completed. The developed framework will serve as a helpful tool in designing and considering different process chains in the manufacture of Titanium components. The manufacturing industry is continuously progressing to become more competitive and more resource efficient. When applying the framework, continuous adjustments are there to be made with regards to technological advancements. Above this, this research will allow the system users and the industry partners produce titanium components more efficiently and be able to possibly compare similar studies to this research.

A framework showing the process of research methodology can be seen in Figure 1 below.

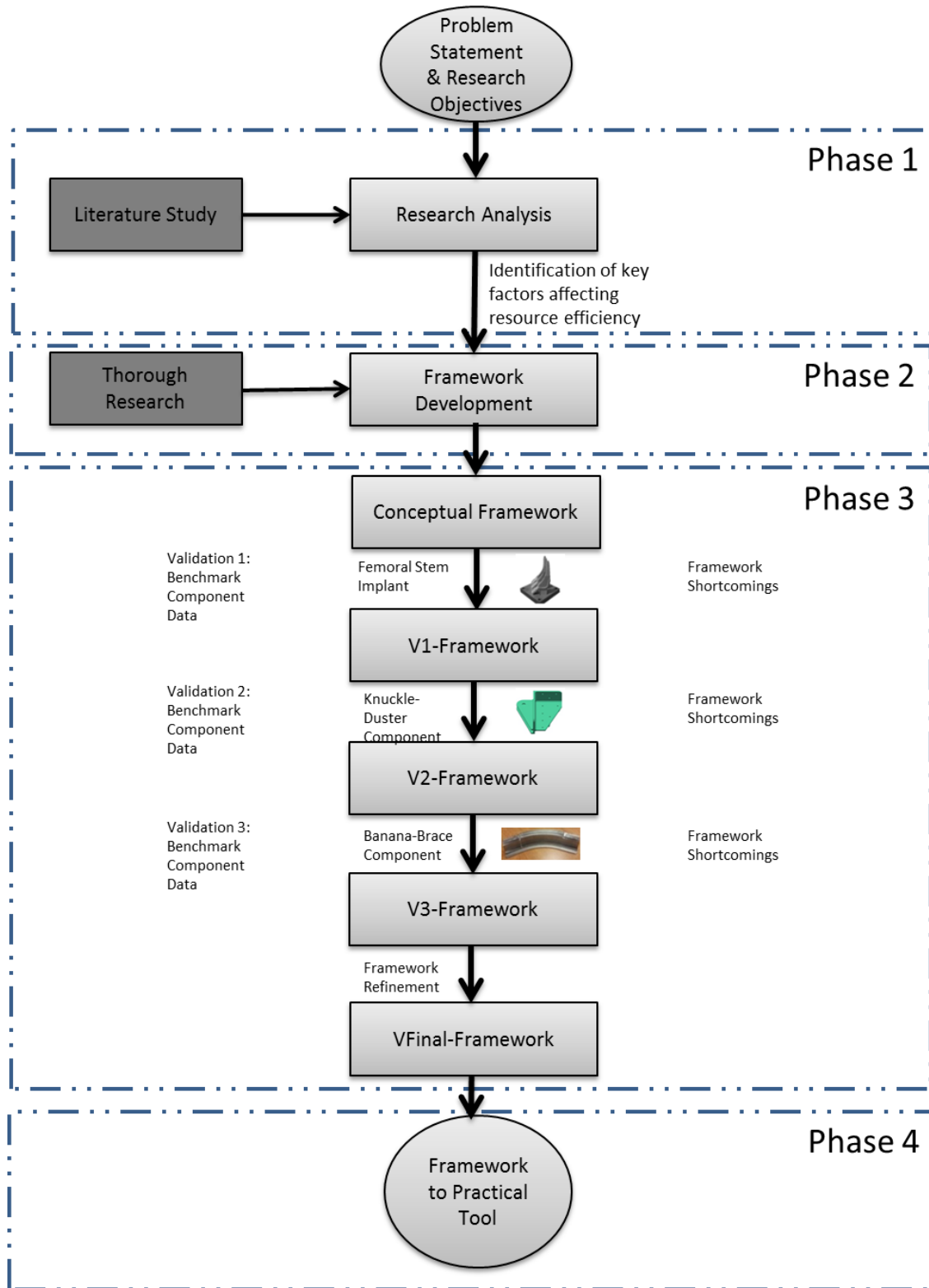


Figure 1: Research Methodology Layout



1.6 Research Roadmap

Included in the prior introduction is an explanation of the background to the presented research, followed by a problem statement addressing the readers as to *why* the research was conducted. A set of research objectives was then described to explain *what* will be gained through the research. Lastly the methodology is presented to show *how* the objectives and goals of the research will be achieved.

Provided in Chapter 2 is Literature review. The basis of the research was gained through the knowledge of previous studies and literature. It begins with an overview of Titanium as a material and Titanium in the South African Industry. From here, the literature focuses on process chains and value streams in order to understand the various factors effecting efficiency and adding value to a process. Following the processes, different manufacturing technologies are researched which can be used in Titanium manufacturing and from here the five most influential factors effecting resource efficiency are discussed.

Chapter 3 present the development of the conceptual framework for investigating the resource efficiency of developed Titanium components. The framework is then validated through iteration one in Chapter 4 in order to find the shortcomings. Chapter 5 presents framework V_1 and its validation through the second iteration. Once the shortcomings are determined, framework V_2 can be developed and validated, as seen in Chapter 6. The shortcomings for framework V_2 are also listed in this Chapter and the final framework for investigating resource efficiency is presented. Chapter 7 shows the user-interface of the practical Excel Based Tool developed to assist the investigation of resource efficient process chains. The tool is validated through the various benchmark components chosen for the research in order for the research to be concluded in Chapter 8 and recommendations for further research mentioned.



2. Literature Review

The following chapter gives an insight in order to achieve knowledge and an understanding of the numerous disciplines that will essentially form a part of the investigations of the research. The chapters are arranged sequentially to elaborate and incorporate the processes that will be involved in order to achieve the problem statement. In order to fully understand the evaluation of the process chains, a brief background for Titanium is given together with its various influences on the process chains.

2.1 Titanium Beneficiation

For the past eight years, the government of South Africa, together with its research industries have been trying to establish a titanium metals industry in South Africa with the purpose of positioning the country as a possible supplier base for both medical and aerospace titanium components and products [18]. Currently in South Africa, there is no downstream beneficiation of Titanium and as a result, South Africa has no potential market further down the value chain [19].

Beneficiation refers to any process which involves the removal of gangue materials from the original ore in order to produce a product which is higher graded known as an ore concentrate [20]. That being said, the beneficiation process in South Africa has allowed for continuous growth in the economy.

Currently, South Africa is the second largest producer of Titanium in the world [21]. Regarding South Africa's titanium industry, substantial value can be gained if these industries are able to operate in areas such as primary metal and mill products, together with downstream components as there are still no downstream industries available [21]. Figure 2 and 3 below show the Value Chain and Product Life Cycle of Titanium respectively from mineral production to the manufactured final product [22]. The entire value chain of titanium expands even further than the final product, which will be discussed later in this chapter.

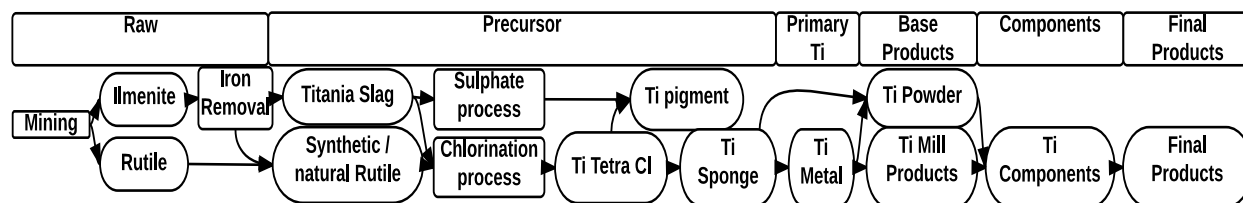


Figure 2: Value Chain for Titanium from mineral production to the manufactured final product (adapted from [22])

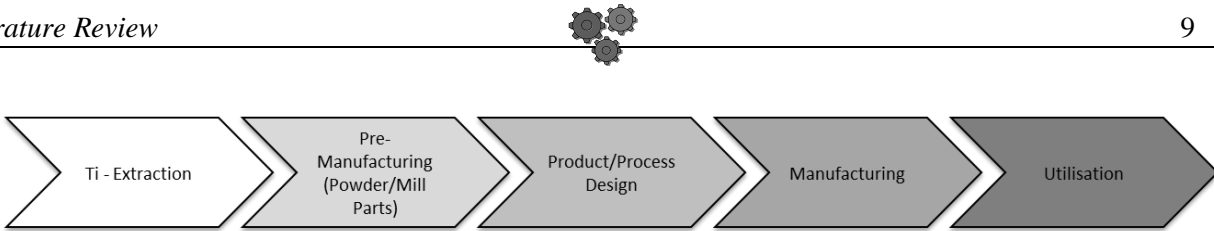


Figure 3: Product Life Cycle of Titanium Components (adapted from [23])

2.1.1 Strategy for Titanium Industry in South Africa

The Titanium Industry of South Africa has a strategy framework that has been developed in order to address competencies, related to Titanium, across the entire value chain of titanium. This strategy believes that South Africa will first enter the market industry with titanium metal powder which will be formulated by a sustainable process that will give the industry a competitive advantage. This strategy is planned to be built on in order to increase the capacity and the capabilities of local industry and to possibly include manufactured mill products, such bar/sheet and plate titanium, together with finished products for the aerospace, biomedical and industrial markets[13].

Figure 4 below shows the envisaged titanium industry in South Africa. Currently South Africa only supplies titanium minerals, thus placing it at the bottom of the value chain. That being said, South Africa still imports the titanium needed for the country at a high cost. This, in turn, causes the manufacturing of the titanium to be reduced due to the extreme prices of titanium products. In order to resolve this problem, South Africa will have to formulate their own in order to produce the titanium metal powder locally [13].

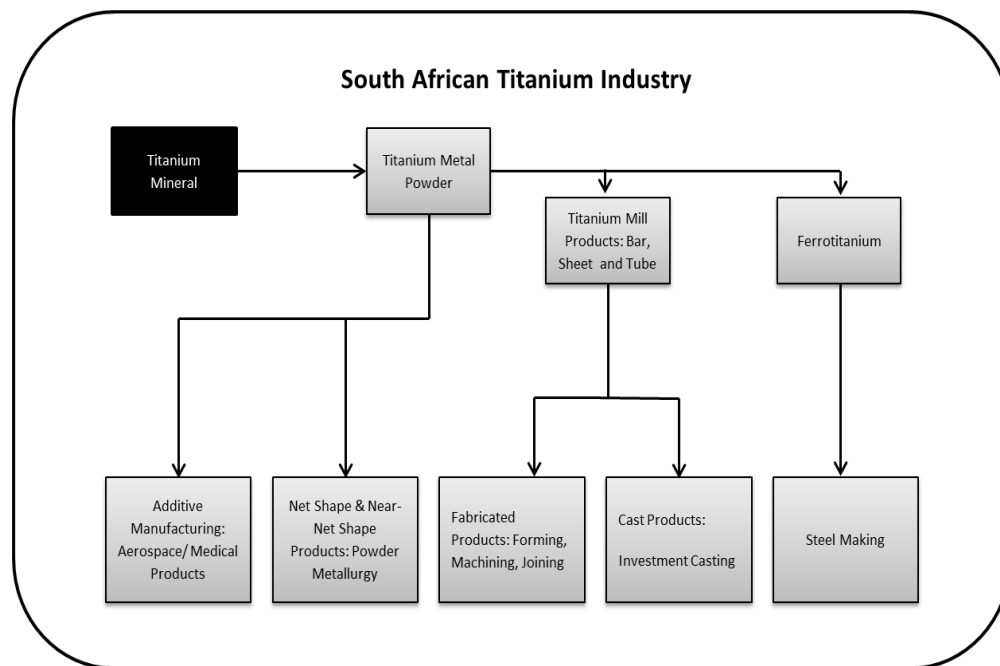


Figure 4: Overview of the envisaged South African Titanium Industry (adapted from [21])



The development and groundwork necessary to implement such a strategy has been carried out by the sponsorship of the Titanium Centre for Competence (TiCoC). The TiCoC is run by the CSIR (Council for Scientific Industrial Research), with the ambition to create and commercialise technology viable for the establishment of the titanium industry in South Africa [24]. The TiCoC operates in a way in which it networks with various research institutions, universities and industrial partners to develop and then collaborate different technology platforms that are essentially viewed as the key building blocks for the establishment of a fully integrated South African Titanium manufacturing industry. The building blocks are illustrated as follows in Figure 5 below.

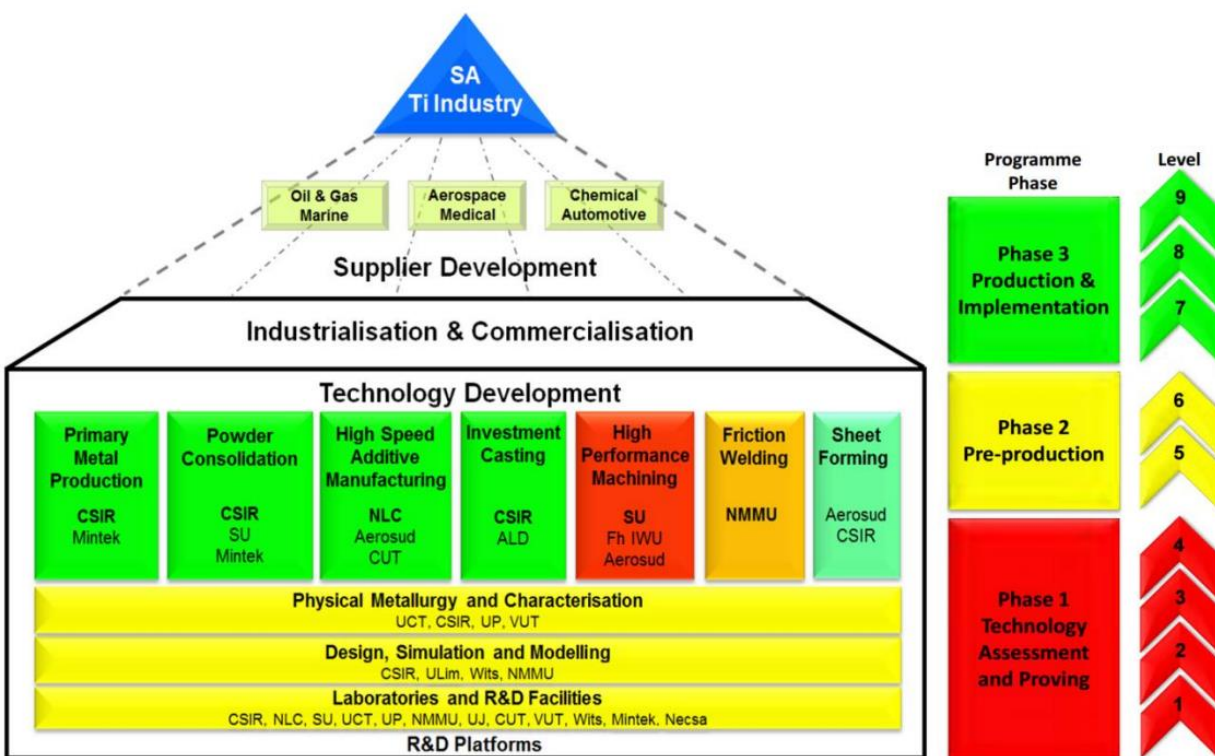


Figure 5: TiCoC - building blocks needed to commercialise and develop the South African Titanium Industry (adapted from [21])

One of the most important building blocks seen in the figure is highlighted in red, the high performance machining of titanium. This building block is focused on the production of finished titanium components that can be effectively distributed to the medical and aerospace industries. The aspects and characteristics focused on in this building block are machine time, material waste reduction and developing more efficient titanium



manufacturing process chains. These technologies and developed competencies can then be distributed to the various industrial partners for practical implementation.

Should the South African titanium industry successfully implement itself, it will too have an effect on the unemployment rate of South Africa as it will create between 750 and 950 new jobs. The plan involves developing new companies in order to produce titanium mill products and titanium metal powder. The metal powder together with the mill products will then be able to be used for downstream manufacturing where they can use the titanium for various procedures to make titanium components essentially. The various types of downstream manufacturing can also be seen in Figure 2 [21].

Titanium is able to be used in many different industries and is always in constant demand. This demand has caused manufacturers and users to shift their focus on cost reduction throughout the value chain: From the extraction of the minerals to the finished titanium product. The strategy for the South African titanium industry thus is driven by the following thoughts:

- South Africa being the second largest producer of the titanium mineral globally with approximately 23% of the worlds titanium deposits but no availability for the actual production of the titanium metal, titanium components, downstream production or mill products [25]
- An exponentially increasing demand for components manufactured from titanium in the medical, industrial and aerospace sectors, all of which show potential for growth in the long term [25]

2.1.2 Influence of Resource Efficiency on Titanium Beneficiation

A key element that effects the resource efficiency of a titanium process chain is the robustness of the part being manufactured as the titanium material has a large influence on this element. The above section proves that the resource efficiency of titanium process chain is largely affected by the beneficiation of titanium. South Africa still imports the Titanium material needed for production purposes. Due to that fact, the cost of the enter process chain will too increase together with the waiting time for the arrival of the material, both of these being another two key elements in resource efficiency of a process chain. These aspects will however be discussed in detail throughout the literature study.

2.1.3 Titanium Applications

The various advantageous properties of titanium allow it to be used effectively in many applications. The reason it is used in so many areas is due to its remarkable properties such as its strength to density ratio. It is the ‘strongest’ of all metal alloys, is lightweight and has high corrosion resistance to the elements such as bodily fluids, sea and water [21] [25].



There are a number of markets in which titanium components are utilised. The most common markets are as follows:

- Oil Industry – Used in drill drafts and pipelines due to its high corrosion resistance and strength to weight ratio
- Naval Applications – its low density and corrosion resistance allow for use in heat exchange equipment
- Armour Industry – Due to its low weight and strength, titanium is used highly in the armour sector (vehicles and plating, also for gun barrels)
- Medical Applications – titanium is a bio-compatible material, meaning when placed inside a body, it does not react harmfully. It can thus be used in both dental and orthopaedic applications
- Aerospace Applications – can be used in the engines and structural components due its wear resistance and the high strength

2.2 *Titanium Alloys and its Applications*

2.2.1 Titanium: Ti -6Al -4V

The Titanium alloy Ti-6Al-4V is an alpha-beta alloy with features such as good corrosion resistance, low weight ratio and a high strength. Currently, this type of Titanium is the most widely used and therefore utilised in a number of areas and applications where high corrosion resistance and a low density is needed, hence the reason it is so popular in the biomedical and aerospace fields [26].

The following three tables below show the composition, physical and mechanical properties of the Titanium alloy Ti-6Al-4V [27].

**Table 1: Elemental Composition of Titanium Alloy Ti-6Al-4V**

Element	Content
C	<0.08%
Fe	<0.25%
N₂	<0.05%
O₂	<0.2%
Al	5.5 - 6.76%
V	3.5 – 4.5%
H₂(sheet)	<0.015%
H₂(bar)	<0.0125%
H₂(billet)	<0.01%
Ti	Balance

Pure titanium either exists as a dark grey powder or a shiny, dark grey metal. As seen in the tables, it has a melting point of $1649\pm 15^{\circ}\text{C}$ as well as a boiling point of $3249\pm 15^{\circ}\text{C}$. Its density often leads to the titanium metal being brittle when cold. At higher temperatures, titanium becomes more ductile and malleable [28].

Generally speaking, titanium is quite unreactive and when at room temperature, does not combine with oxygen.

**Table 2: Titanium Alloy Ti-6Al-4V Physical Properties**

Property	Typical Value
Density (g/cm ³)	4.42
Melting Range (°C±15)	1649
Specific Heat (J/Kg.°C)	560
Volume Electrical Resistivity (ohm.cm)	170
Thermal Conductivity (W/m.K)	7.2
Mean Co-Efficient of Thermal Expansion (0-100°C/°C)	8.6 * 10 ⁻⁶
Beta Transus (°C ±15°C)	999

Table 3: Titanium Alloy Ti-6Al-4V Mechanical Properties

Property	Minimum	Typical Value
Tensile Strength (MPa)	897	1000
0.2% Proof Stress (MPa)	828	910
Elongation over 2 cm (%)	10	18
Reduction in Area (%)	20	-
Elastic Modulus (GPa)	-	114
Hardness Rockwell (C)	-	36
Charpy, V-Notch Impact (J)		24

2.2.2 Titanium in the Medical Industry

Due to the fact that Titanium is extremely corrosion resistant, has high strength to low weight ratio and its composition, mechanical and physical properties all promote bio-compatibility, the use of Titanium in the



medical industry has been revolutionary. This discovery has led to Titanium being utilised in a number of specific applications which involve high reliance such as a hip implant [5].

Currently over 1000 tonnes of Titanium are fitted into patients every year, worldwide. This figure is on the constant rise however as people begin to live longer and thus require more replacements throughout the body. People are also injuring themselves more in the sports arenas and in accident cases [29].

The main reason Titanium is the preferred alloy to be used is due to the fact that it has a significantly higher strength to weight ratio over its main competing alloy, stainless steel [30]. There is too a wide range of Titanium alloys that specialists are able to use, depending on the requirements needed by the patient. This range spreads from cases that require extreme formability and thus need a highly ductile titanium, to titanium alloys that are fully heat treatable with strengths exceeding 1300MPa [5]. Shape memory alloys containing titanium are able to further extend the alloys applications and uses within the medical industry.

2.2.3 Performance of Titanium in the Medical Industry

Whenever any object is implanted/embedded into the human body, the human body's natural reaction is to remove that object. Thus implanting any device to the human body will feel like a potential threat on the body's mechanical, physiological and chemical structure of the body. In most cases, when a metal is implanted into the human tissue, the bodily fluids that surround the metal will cause corrosion. Often this corrosion results in toxic metal ions being realised into the body causing serious health issues for the respective patient [31]. That being said, Titanium is known to be completely bio-compatible and thus immune and inert to corrosion [32]. Following this, another reason why Titanium is the most widely used alloy for medical purposes is due to its ability to join tissue and bone (osseointegration) without causing and creating any potential health risks for the patients [33].

Apart from the above mentioned positive characteristics of Titanium, the alloys low modulus also makes reduction in bone reabsorption possible. Further, another two parameters that complement the alloy is the notch sensitivity, and the alloys propagation of resistance to crack/fracture toughness. Notch sensitivity can be described as the ratio of un-notched tensile strength against notched tensile strength [34].



2.2.4 Titanium Medical Uses

2.2.4.1 Bone and Joint Replacement

There are more than one million people who get treated annually for bone and joint replacements, especially with regards to the knee and hips. These replacements come in many shapes and sizes, depending on the nature of the replacement. The most common are the hip replacement. This joint usually contains a femoral stem and a head and are often are usually layered with a roughened bioactive surface in order to act as a catalyst for osseointegration [5].

2.2.4.2 Dental Implants

A major breakthrough has occurred in the dental industry. Researchers have concluded that Titanium is able to be used as root of a tooth and thus be embedded in the patients jaw bone. A tooth known as a superstructure is then built onto this titanium root [5].

2.2.4.3 Craniofacial and Maxillofacial Treatments

In some cases, patients are able to injure themselves in such a way possible, where the only way possible to treat them is through an implant. Often the causes of these are due to serious skull damage or birth defects.

2.2.4.4 Cardiovascular Devices

In the modern era, Titanium is often used in defibrillators and pacemakers or as the carrier structure for implanted heart valves.

2.2.4.5 External Prostheses

Titanium is often used in case of artificial limbs due to its lightness and strength and suitable for both short and long term fixtures on patients.

2.2.5 Titanium in the Aerospace Industry

As previously mentioned, Titanium's light weight, excellent corrosion resistance and high strength make it the optimal alloy for use in the aerospace industry, as seen in the demand graph in Figure 6. Understandably, the lighter the weight, the easier the aircraft is able to take off resulting in less fuel consumption. Due to the fact that Titanium does have such a good strength to weight ratio, the aircraft is able to be lighter without this affecting the structural integrity of the aircraft [35].

With regards to the corrosion aspect of Titanium, when the alloy is exposed to pure oxygen or air at high temperatures, it develops a passive oxide coating [35]. This coating will continually enlarge itself until it has



reached a thickness layer of up to 25nm (nanometres). This passive oxide layer eliminates all chances of the alloy corroding.

The last important characteristic to consider about Titanium in the aerospace industry is its thermal expansion rate. Thermal expansion causes metal alloys to deform, crack and even fail in cases. Unlike most metal alloys, titanium's thermal expansion rate is low making it ideal for aircraft use due to the fact that aircrafts usually undergo great temperature changes in different climates and at different altitudes.

2.2.6 Titanium Aerospace Uses

There are only two main areas in titanium is used in aircrafts, namely the airframes and the engines of the planes. The need for Titanium use in aircrafts is increasing exponentially however as lighter and more aircrafts are needed for travelling purposes.

2.2.6.1 Titanium for the Airframes

Titanium alloys with strengths of up to 120000MPa have numerous applications in the airframes. Applications from fasteners on the wing to landing gear to actual large wing beams with a weight of up to one ton are all common in aircrafts. Titanium makes up 10% of an empty aircrafts weight [36].

2.2.6.2 Aircraft Engines

Titanium alloys are able to function efficiently in temperatures that range from sub-zero to 600⁰C and thus are used in the engine blades, discs, casing and the shafts. Other components of the engine where Titanium is found are the high pressure compressor, the front fan and at the rear end of the engine such as nozzle and plug assemblies [37].

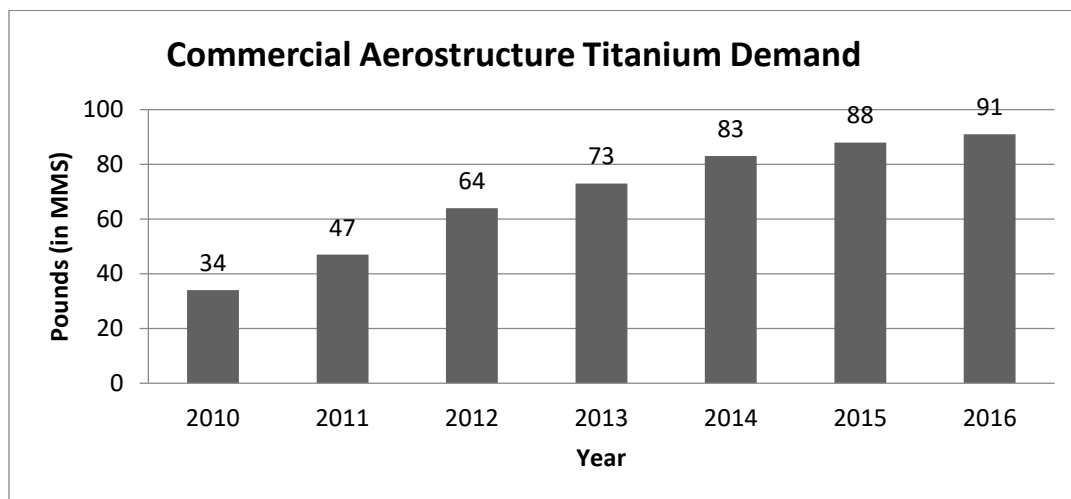


Figure 6: Illustration of the Aerospace increasing Titanium demand (adapted from [38])



2.3 Resource Efficient Process Chains

The following chapter defines what process chains are and how the resource efficiency of a process chain can be analysed both on a process and system level. With regards to resource efficiency from a manufacturing perspective, the efficiency looks at the relationship between resource inputs of the manufacture, together with the product output essentially. Effectively, it illustrates how well the resources in the production line are used in order to add economic value to the product. Single and batch production manufacturing also effects and influences the resource efficiency of a production line.

2.3.1 Process Chain

A process chain can be described as a sequence of events or activities that are scheduled in order to accomplish a certain outcome or goal. In the case of this study, the goal would be to manufacture a titanium component [7].

2.4 Sustainable Manufacturing

In order to achieve sustainable manufacturing, not only do manufacturers need to evaluate the product and the process used to fabricate the product, but they need to span across the entire supply chain. This spanning includes setting up metrics and models for sustainability evaluations and optimisation techniques in order to improve the resource efficiency at both product, process and systems levels [39]. Following this, it is the manufacturing sector which needs the highest level of attention towards sustainability. At a product level, the 6R concept previously mentioned is the basis for sustainable manufacturing allowing products to push through the single life-cycle stage to multiple life cycle stages. At a process level, it is required to achieve resource efficient manufacturing process chains in order to improve the material waste, energy consumption, occupational hazards etc., and to improve the product life by altering and manipulating the surface-integrity of the component/product. At a systems level, it is required that all the major life cycle stages of the product are considered. These stages include: pre-manufacturing, manufacturing, utilisation and post-utilisation [40].

2.4.1 Sustainable Manufacturing Processes

A major setback in evaluating the sustainability and resource efficiency of a manufacturing process is the various indexes used to evaluate these two factors. Many different metrics have been developed in order to evaluate the sustainability and resource efficiency of a manufacturing process. Since there is no defined evaluation system used for investigate the sustainability of both AM and SM processes, recent studies have defined them as sustainable and resource efficient process if the process leads to improved environmental friendliness, reduced wastes, reduced power consumption, reduced cost, improved personnel health and enhanced operational safety [41]. Using this definition a model (Figure 7) has been developed in order for manufacturers to use for the design of sustainable and resource efficient products. Within the six interacting elements, three can be measured using



analytical techniques while the other three elements (safety, environment and health) require measuring them by means of fuzzy logic (non-deterministic) [42].

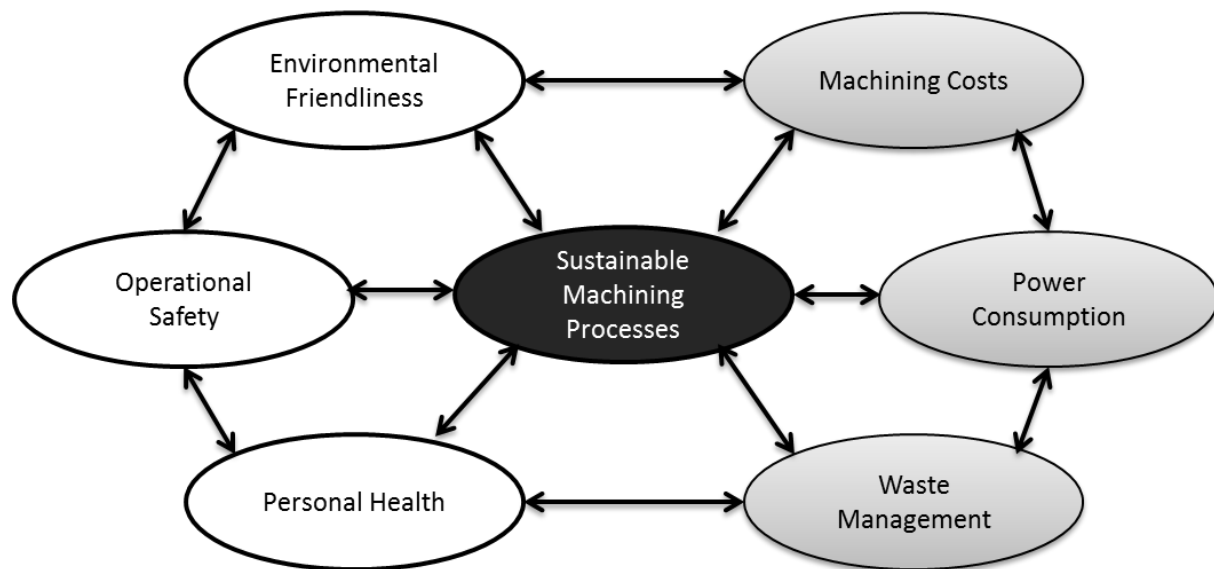


Figure 7: Framework Illustrating the Basic Elements Effecting Sustainable and Resource Efficient Manufacturing (adapted from [42])

2.5 Key Factors Affecting Resource Efficiency for Additive and Subtractive Manufacturing Technologies

Despite advances in AM technologies, several limitations and challenges still exist. A limited selection of software is available for preparation of builds, machine-, material-, and production costs are high, and anisotropy in the microstructure can lead to differing mechanical properties [43] [44]. In addition, more skilled personnel are required, leading to higher operator costs. Several trade-offs should therefore be considered when investigating the adoption of AM into existing process chains. Research opportunities also exist for each of these factors which can individually be optimised in terms of its influence on the overall resource efficiency. Through research of many different manufacturing processes and experiments it is seen that the key factors affecting the resource efficiency of a manufacturing process chain are namely:

- Material Waste
- Manufacturing Costs
- Manufacturing Time
- Quality Control (Accuracy)



- Energy Consumption

By correctly managing the above mentioned factors, manufacturers will reduce resource consumption and costs. Each of the factors affecting the efficiency are explained in the Chapters below.

2.5.1 Material Waste

Material waste has a large impact on the resource efficiency of a process. Regarding the AM process, material waste can essentially be reduced by optimising build supports or in areas involving the design and build orientation. Contamination of the produced parts also has an influence on wastage, as dust or debris could pollute the part being manufactured. Material waste in context of the subtractive manufacturing can be calculated as the volume of material removed from the solid billet when manufacturing. Conventional processes such as drilling, turning and 3- and 5-axis milling have a buy to fly ratio of 10-25:1 [45] [46]. This means that during these subtractive processes, up to 95% of the original billet material is machined away and left as formed chips. The time required to remove the material from the starting billet adds significant cost to the process chain in terms of the raw material, tool life and machining time. This thus essentially motivates the use of AM strategies which yield a buy to fly ratio of 1-7:1 [47] [46]. That being said, the geometrical accuracy and part finish to AM strategies are usually inferior to that of CNC processes.

A major benefactor for manufacturing parts using AM is that far less material is used when compared to the subtractive manufacturing process, thus resulting in less waste. This is due to the fact that, as identified above, AM uses a layer-by-layer approach, causing little to no waste material. This however understandably depends on defects or contaminations of the part produced. Below, an illustration of the material removed and costs for additive and subtractive manufacturing is shown to provide a more thorough understanding.

Recent studies have ever shown that the product-life-cycle of the component with regards to material waste has large impacts on the sustainability of the ecological footprint. These life cycles of perpetual material flow thus have significant impacts on the resource efficiency of the manufacturing process. The 6R concept of modern manufacturing has made huge progresses in terms of the sustainability of the environment together with the resource efficiency of manufacturing process chains. The 6R's are namely; reduce, recycle, recover, redesign and remanufacture.

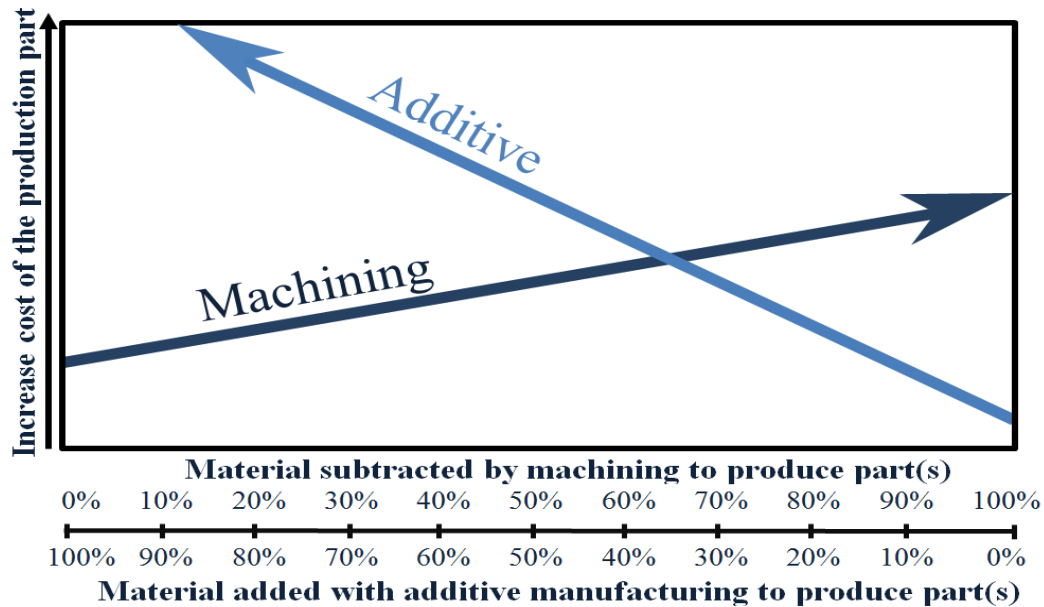


Figure 8: Illustration of the relationship between the costs and amount of added or subtracted material (adapted from [48])

- *Reduce* refers to the different actions and activities used in the designing of the component in order to seek simplification of the current design in order to facilitate second-hand use.
- *Reuse* similarly to reduce, refers to the way in which the product can still be used in the post-life cycle stage.
- *Recycle* understandably refers to the different ways the component can be shredded, separated or smelted for example, so that the material can be used again in a different manufacturing process.
- *Recover* involves the activities of collecting components that have reached their ‘end of life’ so that they can be used in subsequent post-use activities. It also refers to the dismantling and disassembly of the components at the their end of life phase
- *Redesign* cooperates with the *reduce* category as is involves the simplification of the component essentially in order to facilitate post use processes.
- *Remanufacture* refers to the new manufacturing methods and processes performed on the used product

By including the ^R’s of manufacturing into any manufacturing process, the resource efficiency for future components to be developed will increase and so too will the sustainability of manufacturing.

2.5.2 Manufacturing Costs

Manufacturing costs, which can be defined as the material, overhead and labour costs of producing a complete product is one of the most significant qualities and factors that need to be monitored for a manufacturing



process. A large portion of the representation of efficiency is evaluated through the manufacturing cost per unit of components. If any of the overheads, material or labour costs are too high, changes need to be made in the process chain and action must be taken. If labour is too high, employee numbers, procedures, or the tools of the process must be altered in order to control cost of the process. For materials, correct planning must go into all manufacturing process chains as well as the 6R evaluation system in order to eliminate the waste of expensive raw material, like Titanium. This in turn will maximise productivity of the each component. In terms of overheads, managers should simply create a working environment in which it develops only components that are needed. In order to calculate the costs of the various process chains used to manufacture the components, material, machine and labour costs needs to be considered [49]. These will be the prices quoted from the CSIR, IAT (Institute of Advanced Technology) and the RPD Labs of Stellenbosch.

The quotes requested will show the hourly rates of the various processes used during the manufacturing of the component. The equations below can be used to calculate the manufacturing costs.

$$\begin{aligned} & \text{Direct Material Costs} + \text{Material Overhead Costs} & (1) \\ & = \text{Material Cost of Process} \end{aligned}$$

$$\begin{aligned} & \text{Direct Manufacturing Costs of Processes 1 to n} & (2) \\ & = \text{Total Direct Manufacturing Costs} \end{aligned}$$

$$\begin{aligned} & \text{Machine Dependant Indirect Manufacturing Cost of Process 1 to n} & (3) \\ & = \text{Machine Dependant Cost} \end{aligned}$$

$$\begin{aligned} & \text{Specific Direct Cost of Process} + \text{Residual Process Cost} & (4) \\ & = \text{Manufacturing Cost of Process} \end{aligned}$$

$$\begin{aligned} & (1) + (2) + (3) + (4) \\ & = \text{Total Process Cost} \end{aligned}$$

Through literature analysis however, there are more detailed cost models that have been derived in order to correctly calculate the manufacturing costs of developing a part. Gibson, Stucker and Rosen developed an AM cost model approach in order to estimate the costs associated with an additive manufacturing process. Regarding the cost model, four main cost areas for AM were identified namely the operating costs (C_o), material costs (C_m), the machine purchase price per part (C_p) and the labour costs (C_l) [50]. The sum of the above mentioned will essentially calculate the total AM cost of a part, as seen in formula (1) below.

$$C_{\text{manufacturing}} = C_m + C_p + C_l + C_o \quad (5)$$



The machine purchase price per part is the following cost to consider when referring to Gibson, Stucker and Rosen's model. In order to calculate this cost, the purchase price of the machine, together with the machine life (Y) and the build time in hours (T_b) of the part need to be known. The calculation for this cost is derived in formula (2) below.

$$C_p = \frac{\text{Purchase Price} \times T_b}{X \times 24 \times 365 \times Y} \quad (6)$$

Where (X) is the percentage up-time of the machine (percentage the machine is used building during the year). Understandably, (24×365) accounts for the number of hours in a year [50].

Operation costs are simply a multiplication of the build time of the part and the cost rate (C_{rate}) of the specific AM machine being used. Cost rates for a specific AM process include machine maintenance costs together with utility costs and energy usage costs. The calculation for the operating costs can be seen in formula (3) below.

$$C_o = T_b \times C_{rate} \quad (7)$$

The final cost to calculate with this model is the material cost. This is also a simple calculation whereby the cost is derived by multiplying the cost per unit of material (C_u) together with the number of units of material used in the manufacturing process (C_m) [51].

$$C_m = C_u \times U_m \quad (8)$$

2.5.3 Manufacturing Time

When referring to the manufacturing time of a process, the cycle time of the process effects the resource efficiency in a major way as it contains the information which allows manufacturers to know the available production process capacity. To add to that, a common phrase that is thrown around the manufacturing industry is that time is money, which is true as illustrated with the previous trade offs.

With regards to literature studies, standard timing procedures occur in order to calculate the manufacturing/processing time of part. When a number of parts are together involved in a production process, the operation times of the specific parts must be recorded separately for each different part as its own processing time. As a manufacturing regulation, processes producing parts in batches or processes with continuous flow are the ones in which usually alter the products material properties [52]. For example, in production engineering these processes are namely cleaning or casting by means of varnishing, heat treatment or sandblasting. These



processes often have longer residence times than primary production processes such as forming, shaping and assembling. That being said, the processing and manufacturing times of a production process in process engineering vary from the operation times in actual manufacturing processes and thus should be documented differently. In addition to the mentioned processing time, the batch size of the production must to be recorded showing the process quantity. Standard times viewed from a manufacturing perspective are recorded such as the time to manufacture, the setup time, programming time where necessary and the waiting time. Other times such as actual build time, pre- and post- processing times are measured in order to incorporate the entire process chain. These times are simply added to one another in order to calculate the total time of the manufacturing process chain.

In order to calculate the cycle time, for single or for batch production, two formulas are respectively considered.

$$1. \quad CT = \frac{OP \times \#P}{\#Res} \quad (9)$$

$$2. \quad CT = \frac{PT \times \#P}{PQ \times \#Res} \quad (10)$$

Where: CT – cycle time

OT – operation time

PT – processing time

PQ – batch production for process quantity

#P – number of parts for finished product

#Res – number of same resources

Another method to use in order to calculate manufacturing time will be that of utilising a standard timing procedure of each different process in the manufacturing process chain. This will too essentially indicate to the produce where the possible bottleneck of the process is in order to further optimise the bottleneck and improve the resource efficiency.

When evaluating manufacturing time from a business and industry perspective, the factor makes up a large portion of the production lead time. Lead time refers to the time taken from the moment an order for the component is placed until the component is placed in the hands of the customer [53]. The characteristics that



make up lead time are the pre-manufacturing time, manufacturing time, waiting/queueing time, transportation time, storage time and inspection/quality check time. There are various ways in which lead time can be reduced such as reducing the non-value adding procedures by value stream mapping, or simplifying the parts/reducing the complexity, or standardising the operations in order to reduce the staff confusion.

Another important aspect to consider when evaluating the manufacturing time of a process is the machine downtime limitation. There are occasions where resources in the manufacturing process chain are unavailable due to maintenance or unforeseeable technical malfunctions resulting in a hindered process performance. Other factors and losses that can be compared to the downtime of a manufacturing process are times losses, speed losses and quality losses [10]. The time losses are a result of equipment breakdown due to factors such as the operating personnel or malfunctions. Speed losses of the process happen due to minor stops or fatigue in the equipment resulting in a slower manufacturing time than usual. These minor time delays are often dealt with hastily by the operators. Due to the fact that these speed losses are often relatively short when compared to the manufacturing processes, these delays are not documented and thus not noted as a factor effecting resource efficiency. Quality losses come as a result of starting losses and component defects, followed by compensatory production and reworks.

2.5.4 Quality Control

Due to the fact that the common aim in manufacturing is maximising profit and minimising cost, the quality of the product being produced is often an issue when trying to fully adhere to the requirements of the customer. Often products are developed in a time frame that isn't, in standard cases, possible, resulting in defects and in turn, material waste.

When building functional parts with AM or traditional methods in either batch or single sizes, it is important to perform detailed non-destructive inspection, as defects might still be present. Most notably these include; residual porosity, internal cracks or insufficient fusion of layers, surface cracks or inadequate roughness, geometrical distortion due to inadequate support structures, and geometrical deviation and delamination due to residual stresses. Internal inspection can be performed by computed tomography scanning in order to determine components such as failure analysis, assembly analysis and the metrology of the part. Geometrical inspection of the produced part can also be examined by tactile processes such as co-ordinate measuring or optical scanners. These measuring systems are capable of measuring accuracies of $1\mu\text{m}$ with speeds of covering measured part at 150mm/s which is equivalent to measuring 200points/s [54] [55]. This though is a challenging factor for reducing resource usage when producing single parts as both time and money are used. For batch production, however, a statistical sampling strategy could reduce time and cost for inspection.



2.5.5 Energy Consumption

Energy Consumption is another major element affecting resource efficiency. According to Bunse *et al*, worldly, the manufacturing sector is the leading consumer of energy. As much as 33% of the total energy is consumed by manufacturing processes [56]. Price for energy is on the constant rise as energy is becoming more and more in demand. This constant rise has had many effects on organisations energy schemes as calculating the energy costs become more complicated every year [57].

Through research it was found that energy usage for different manufacturing technologies varies and depends greatly on the production volume. It is necessary to divide the energy efficiency into different levels. As seen in the figure, the most important factors effecting energy efficiency are outlined. The lowest level is the process level, which refers to the loss of energy regarding the physical mechanisms of the process. The next level is the machine level. Although the machine does use energy during the process itself, it also spends energy on the peripherals of the process. It is important to separate the process and machine level as energy losses are caused by different technologies and mechanisms. Finally, you have to consider the production line level and the factory level of the process. Here energy efficiency comes as a part of production planning of the system in order to develop resource efficient processes [58].

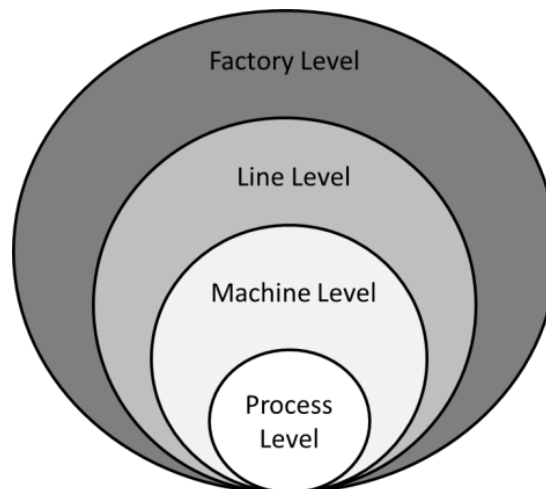


Figure 9: Illustration of the different levels of Energy Consumption (adapted from [59])

With regards to the energy efficiency using conventional and non-conventional methods, there are many factors affecting the output energy of the process. For example, looking at conventional methods, the energy used can be calculated looking at the ratio of the volume of energy removed from the billet to the amount of energy spent. A trade-off that has been evaluated in many experiments is that it is evident that the faster the process and the feed rate velocity, the more energy efficiency the process is [59]. Looking at the non-conventional AM processes,



there are a wide variety of applications that these technologies can perform, such as welding or cutting etc. Due to the many variations and functions of the technologies, the energy efficiency is calculated with regards to the specific process and its goals. Energy losses with non-conventional methods are however always present due to factors such as material reflectivity off the work piece, defocusing of the laser beam (when the laser does not focus on the optimal position, resulting in absorption of the energy by non-target regions and by heat conduction of the build [60]. At a machine level with regarding the AM processes, it is defined that energy efficiency is a dimensionless number as the calculation states that the energy is calculated as the ratio of energy provided to the process to the energy consumed by the machine. A major factor that is not usually considered during the process is the amount the peripherals effect the energy consumption. Often manufacturers ignore the amount of energy being used between the peripherals that are always turned on and the peripherals that depend entirely on the machine load [61].

As seen in Table 4 below, a summary of various manufacturing strategies energy usage is given from different researchers with specific reference to the method of manufacturing used and the Mega Joules (MJ) per kg of material used. The data has been captured through experiments, observations (empirical measurements) and literature studies (non-empirical measures) according to the authors.

Table 4: Table showing a summary of different energy outputs from different manufacturing strategies (adapted from [62] [63] [64] [65] [66])

Study	Technology Variant	Energy Consumption Result	Methodology
Luo et al. (1999)	Stereolithography	74.52 - 148.97 MJ/kg	Not empirically measured
	LS	107.39 - 144.32 MJ/kg	
	FDM	83.09 - 124.04 MJ/kg	
Mognol et al. (2006)	3D Printing	7.56 - 13.68 MJ per part	Single part build experiments, various orientations
	FDM	1.80 – 4.50 MY per part	
	DMLS	115.20 – 201.60 MJ per part	
Sreenivasan and Bourell (2009)	LS	52.20 MJ/kg	Not empirically measured
Kellens at al. (2010)	LS	129.73 MJ/kg	Full Build
	SLM	96.82 MJ/kg	Experiments
Baumers et al.(2010)	SLM	111.60 – 139.50 MJ/kg	Single part & full build experiments
	EBM	61.20 – 176.67 MJ/kg	



As seen from the above table, energy consumed throughout the manufacturing processes of both single and batch productions is a large amount and thus heavily effects resource efficiency in more manufacturing process chains. In order to calculate the energy consumption of manufacturing processes both a theoretical and definite calculation can be performed. Theoretical in the form of evaluating the energy consumption by calculating the energy consumption based on the literature of how much energy each different type of additive or subtractive manufacturing machine uses when in operation.

2.5.6 Resource Efficiency in Production Systems

Today, in many manufacturing systems, resource efficiency is a common issue and manufacturers are often lazy and careless in terms of energy and material efficiency of the process [67]. Recent studies have shown that there has been an increase in global energy consumption of between 40 and 50 percent in the year 2015, with at least 33 percent of that energy use coming from the manufacturing sector [68]. A common link to resource efficiency is that of sustainable development. Sustainable development typically refers to instances where resources are controlled to the amount of how they regenerate themselves naturally, in simpler terms, keeping resource consumption below the resource generation rate. With constant energy growth in mind, sustainable development can now easily be linked to resource efficiency and process optimisation. If these manufacturing process can be kept resource efficient and optimised, the consumption of resources can in turn be reduced resulting in an energy and material decrease [68].

Manufacturing, in term of resource efficiency, can be classified into different levels. These levels vary in efficiency and come in the form of machine level, factory level, line level and process level. In this research study, process level will be examined [69].

2.5.7 Process Level Resource Efficiency

Material removal is an essential part in the process class. There have been many case studies concerning the energy efficiency of machining processes, some of which have actually defined energy efficiency as the ratio of the energy spent to the amount of material removed. Some case studies too defined the energy efficiency as the ratio between the volumes of material removed to its process parameters [70].

A significant understanding between the case studies proved to be that if the manufacturing time of the process decreases, a positive impact occurs concerning the energy efficiency. In order for manufacturing time to decrease, the feed rate of the process has to be increased. Understandably, by reducing the manufacturing time, quality of the finished product has a higher chance of decreasing and by increasing the feed rate of the process, so too will the tool wear increase.



That being said, all manufacturing processes differ from one another in terms of the key elements of the process chains such as, robustness, quality of the finished product, the costs incurred of the process. Hence, again the reason for this study.

2.5.8 Business Level Resource Efficiency

At business level, traditionally an enterprise would have most of their focus on the factors that directly affect their performance economically, with the main focus areas on the profit margins, sales and the cost of the sales [71]. That being said, businesses nowadays are taking a different approach to the way in which they feel their efficiency should be measured. Many businesses are structuring themselves toward sustainability for their resource efficiency, and how their business relates to the surrounding environment and community. This aspect allows the business to analyse the actual impact they have on community and physical environment. Most businesses look at impact they have on the people, plant and profit. By improving resource efficiency in terms of sustaining these three factors, business will not only improve their profit margins as a whole, but reduce their carbon footprint for the future use of the world. Many business have strategic frameworks they follow in order to improve the resource efficiency of their company [71]. These frameworks include aspects such as implementing lean systems across the whole business, highly training the personnel, implementing leadership strategies for sustainable practices, identifying how to reduce waste, optimising production processes, supply chain management, improving daily operations, developing the company for the 6R concept and identifying how to reduce downtime and reworks [71].

2.6 Single Part Production

Single part production takes place when only one part is produced during a manufacturing process. This type of production is usually only utilised when a very large part is needed to be manufactured, the part that is required has complex geometries or it is just not feasible to manufacture more than one part. Following this, costs per unit production are usually higher than that of the batch production which is discussed later in the chapter.

As seen in Figure 10, the quantity vs quality distribution is represented. Understandably with an increase in quality, there is a decrease in quantity and vice versa. However, that being, this is not always the case. If a mould is used during batch production, the quality of the output products rarely differ from single part production [72].

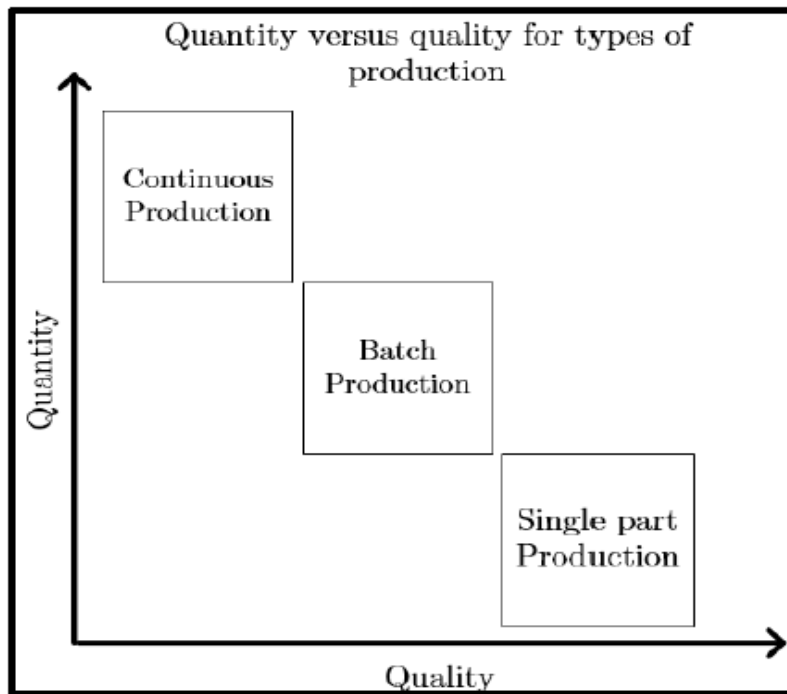


Figure 10: Quantity vs Quality Graph for Single and Batch Production (adapted from [73])

2.6.1 Batch Production

When manufacturing processes produce parts simultaneously or more than one part of a specific product is consecutively manufactured, batch production occurs. There are many ways in which batch production can occur and also many different applications. The different applications each have a certain benefits depending on how you evaluate them. An example of an additive manufacturing process for batch production would be that of developing a number of parts using the Selective Laser Melting (SLM) machine where the parts can be placed on the base plate and then produced together simultaneously [72]. Depending on the design of the parts that need to be produced and the build orientation of the parts, production costs and production time can be increased, however, when the build orientation is 'optimal' and no specific designs are needed, there will be no increase in in time, costs or energy consumption. A second example of a manufacturing technology in batch production can be the use of the CNC (Computer Numerical Control) machine. This can occur when the parts that are required to be manufactured can be placed all on the same biller and then machined while on the billet [73].

Batch production is commonly used in cases where the requirement for the part needed is not customer specific and thus a mould can be used. As previously mentioned, the most common technologies used for batch



production are the CNC and SLM machines due them being able to manufacture parts simultaneously. When batch production is successfully implemented, the production cost per unit will be decreased respectively.

2.7 Value Stream of Manufacturing Processes

Creating and analysing a value stream in a manufacturing process allows manufacturers to chart material flows during the manufacturing process. This essentially demonstrates the sequence of how different products pass through different resources (process chain), allowing for the opportunity to evaluate and determine how well the resources and materials match the layout of the process chain developed. This is however changed when batch production occurs as overlapping of value streams is possible [10].

With regards to the resource efficiency and manufacturing process chains, a method has been developed which visualizes and analyses material and production flows/processes together with combining the analysis of information flows. This method developed is known as the value stream method (VSM) and is used to essentially map the various manufacturing process chains, either in a small manufacturing plant or factory in order to increase the internal communication within the process [10]. By following the VSM, it will allow users to increase the resource efficiency of the production by increasing the transparency of the manufacturing processes, as opposed to single machines being used individually throughout the production process. With regards to the actual name, *Value Stream Method*, the word “value” refers to the amount the manufactured part will actually contribute, in terms of from a source material to a component of higher nature, which, in this studies case, is the amount of importance a medical or aerospace component will be. The word “stream” refers to the process chain of the component being developed and the flow of production. For obvious reasons, the different steps in a process chain cannot be piloted at the same time, which allows for resource efficiency and value stream analysis [10].

Other methods such as sigma six and PDCA (plan do act check) are also frequently used in manufacturing systems in industry. Similarly to the value stream method, sigma six looks at process improvement and seeks to improve the quality of the actual process by identifying and eliminating defect causes as well as reducing the variability of manufacturing [74]. Six sigma projects and usage follow two different methods, which are inspired by the PDCA cycle. These two methods are composed of five phases each and are referred to as DMAIC and DMADV.

The DMAIC acronym stands for:

- *Defining* the customer voice and their requirements, the process system and the project
- *Measuring* the key factors of the process and collecting the relevant data



- *Analysing* the collected data and evaluating the different trade-offs between the such data and verifying their cause-effect relationships
- *Improving* or optimising the current process chain using design for experiment techniques
- *Controlling* the future process chains to make sure that any deviations have been corrected so that no future defects may occur. By implementing control systems the quality level desired can be obtained.

The DMADV acronym stands for:

- *Defining* the goals needed to satisfy the customer
- *Measuring* and identifying the CTQ's of the process chain (critical to quality), measuring the process and product capabilities, and measuring the risks
- *Analysing* to design and potentially alternative processes
- *Designing* an alternative process
- *Verifying* the design and setting up potential pilot runs

By performing these steps and methods in a manufacturing process, common industry outputs to using the technology are reduction in cycle time, increased profits, increased customer satisfaction and a reduction in costs, all leading to a an improvement in the resource efficiency aspect [75].

Just like six sigma and the value stream method, PDCA (Plan-Do-Check-Act) is a management method used to in industry for controlling and improving process chains and products. Usually the PDCA method is iterated over and over until the process problem is solved and optimised, as seen in the figure below.

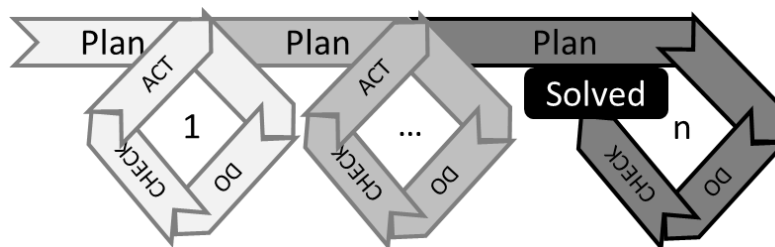


Figure 11: Iterations of the PDCA cycle (adapted from [76])

With regards to the ‘Plan’, it refers to the way in which manufacturers should first establish the different processes and their objectives required to deliver the results of the expected goals and outputs of the process. Looking at ‘Do’, it refers to the implementation of the process in order to produce the product, and to collect the data for the analysis to complete the ‘Check’ and ‘Act’ steps. Approaching the ‘Check’ step, manufacturers



should study the results collected in the ‘*Do*’ step and compare the results and data to the goals and objectives set out from the ‘*Plan*’ step. Manufacturers, should then evaluate the deviations of the data in order to determine where implementation changes from the plan occurred. If the ‘*Check*’ proves that the ‘*Plan*’ applied in ‘*Do*’ is an improvement to the previous manufacturing strategy, then that becomes the new standard base manufacturing approach for how the manufacturers should ‘*Act*’ in the future. If for instance the ‘*Do*’ steps were not an improvement, then the existing process will remain. In a case where the ‘*Check*’ showed something unexpected whether it be better or worse, there is still learning to be done on the process [76].

2.7.1 Component Value

The value of a component is seen as the amount the part will contribute when manufactured and its end part characteristics. The value of a component is thus able to be determined through evaluation techniques by certain evaluation criteria. That being said, there are many different trade-offs that need to be considered when developing a component needing to be manufactured. These trade-offs include costs, manufacturing time, profit margins, accuracy, etc. all of which effect the final value of the produced part. When developing a part/component for a client, customer satisfaction is the first aspect a manufacturer wants to achieve. In order to achieve this goal, the value of the end product needs to be high whilst maintaining manufacturing trade-offs to a minimum. Following a certain method of manufacture will ensure a positive value stream for the manufactured component, thus resulting in a resource efficient process effectively [10].

2.7.2 Component Stream

When referring to the value stream of manufacturing process, the flow of the production within the stream is considered as one of the decisive characteristics into performing a positive process and is seen as the key aspect into evaluating the efficiency of the process. The value stream principally incorporates all the tasks and the procedures in the manufacturing of a raw material into a fully finished product [10]. The task and procedures of the value stream include:

- All the manufacturing and production procedures, i.e. the tasks changing the raw material to a finished product. These tasks can be broken down into 6 main manufacturing groups:
 1. Primary Shaping
 2. Shaping
 3. Separating
 4. Joining
 5. Coating
 6. Alteration of substance properties



- The logistical aspects of the manufacture such as material storage, material delivery, handling of the material, supply of the material and commission involved in the manufacture
- The indirect tasks of a manufacture such as preliminary planning of the process, planning the control of the process, maintenance and upkeep of the manufacturing machines.

The tasks mentioned above are all not necessarily value adding tasks however. The decisive criterion for a value adding task is whether or not a respective task can be used to give the manufacturing component or product a value-enhanced characteristic. Thus, a major aspect that needs to be considered in the manufacturing environment is the continual optimisation of different processes in order to eliminate or reduce no-value adding processes. This in turn will have a major impact on the resource efficiency of the process chains [10].

2.7.3 Four Goals of a Manufacturing Process

When optimising a production process, the first question that is always asked is to which goals the optimised processes should be compared against and measured up to. When the goals of the process are achieved, they indicate the efficiency and quality of the process. The primary goals of any production or manufacturing process are to shorten build times, produce high quality products and to lower manufacturing costs. That being said, the efficiency of manufacturing process is determined by four common goals. These goals are namely economy, speed, quality and variability as illustrated the Figure 12. Each goal dimension listed above includes its own partial goals which reciprocally define the efficiency of the production system [10]. These goals sometimes conflict with one another and thus can effectively be seen as trade-offs. For instance, quality goals may not be met if the manufacture goal is for a reduction in time, understandably.

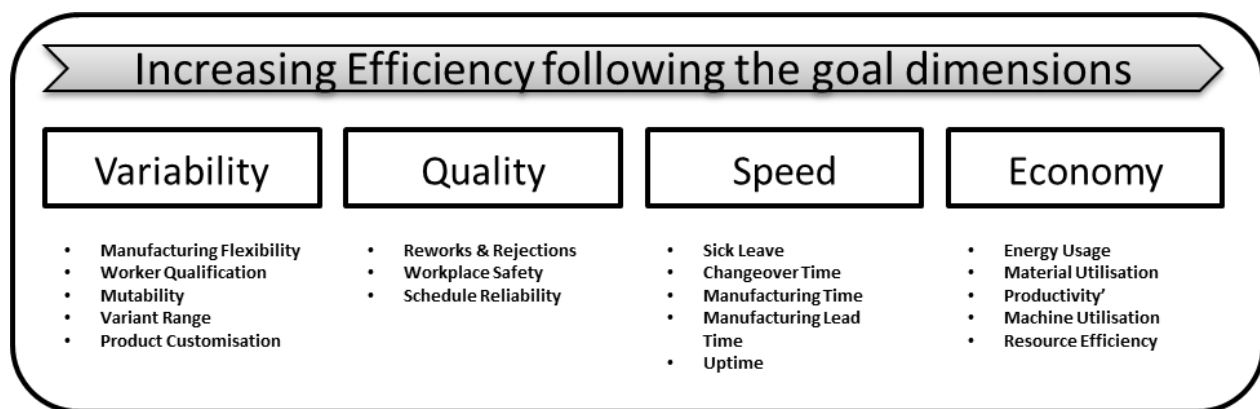


Figure 12: Goals for achieving resource efficiency in a manufacturing process (adapted from [10])

The sequence illustrated in the figure does not necessarily represent the significance of the goals. The significance of the goals varies for each specific type of production.



For example, when looking at a manufacturing a medical component achieving the quality goal will be the most important as it needs to be perfect in order to be compatible for its specific utilisation. The sequence does however show the logical manner for outlining the goals needed in each goal category. Thus, when manufacturing a component, you should begin with outlining the actual product range and the reasoning behind the production in order to understand what is needed to achieve customer satisfaction while manufacturing resource efficiently [10].

Variability in the figure refers to the range of the manufacturing process. The variability dimension determines how many variants and trade-offs will be created and for what specific component needing to be manufactured. The flexibility dimension refers to what extent different processes are able to be used in order to use the best or most resource efficient process for example the utilisation of hybrid processes essentially. Mutability in this case refers to the way in which manufacturing processes are able to change to new requirements.

Following this, the quality of the production determines the yield rate of the manufacturing process. On the other hand however it refers to how well the levels of tolerance are complied with together with the reliability of the actual production process.

The speed of the manufacturing process shows how much time is consumed when performing the value adding process steps as well showing the time taken for change overs or pauses in the build. The availability of the various manufacturing machines is also taken into account in order to indicate frequency of the machine use and the breakdown duration, which consequently affects the production efficiency.

The final goal, economy, illustrates the productivity of the process in relation to the different production factors. Branching from this, all the costs involved with quality, variability and speed are identified.

These goals do often collide with one another in some way or other [10]. The optimisation of manufacturing processes will continually strive to achieve resource efficiency even though conflict between the above goals is inevitable, though, bearing in mind, the importance or weighting of different goals does change over-time with different technology and research advancements.

2.7.4 Goal Conflicts/Trade-Offs

As previously mentioned, the goals do sometimes conflict with one another due to the specific criterion needed for either the customer or the manufacturing process. These four goals previously mentioned can thus be developed into a logical representation of how each goal or trade-off effects another. Figure 8 represents the relationship and the trade-off each of the goals have with one another and is shown through the ‘conflict lines’, as seen in the Figure 13 [10].

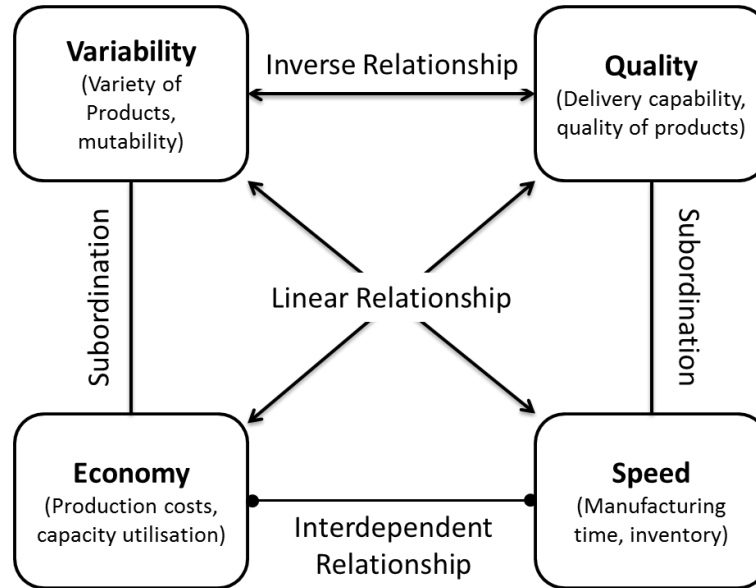


Figure 13: Trade-Offs of the resource efficient goals (adapted from [10])

- With regards to the trade-off between quality and economy, the conflict line refers to mutual, linear relationship they share. If the quality improves, so does the cost of the process. Understandably, heightened product quality means more skilled precise work needs to be performed, together with more costly resources and quality assurance/control. Essentially, if one does not adhere to additional expenses mentioned above, the material wastage and scrap cost will increase due to the fact that fewer of the enhanced quality parts will be within the given tolerances. A common feat is where batch production is used in order to increase economy so that there is better all-round utilisation. However, logistically speaking, this does decrease quality due to the fact that batch production does lead to longer waiting times during manufacturing process, thus decreasing resource efficiency.
- When examining the relationship between variability and speed, the conflict line shows that an increase in variability will have a direct effect on speed as well, leading to longer manufacturing processes. Generally speaking, the greater the number of variants and the greater the customisation of the product, the longer the manufacturing process of the product. In order to resolve the conflict between these two goals, a strategy of in depth process planning before manufacturing should be considered in order eliminate possible variants that may arise during the process.
- The conflict line between variability and quality represents the trade-off indicating that with an increasing variability of the product causes a difficulty trying to achieve the quality goals. That being



said, an increase in quality requirements for the product causes both flexibility and variability to be restricted. When looking at this relationship through a manufacturing perspective, an increase in the variability of the product will have a direct effect on the demand for the different production systems needing to accommodate the change thus causing poor quality of manufactured parts.

- With regards to the relationship between variability and economy, the trade-off indicates that it is usually for productivity to improve rather than increasing the production range. This means that resource efficiency will be achieved by reducing the manufacturing cost of the process rather than trying to change the process chain to a more flexible one to accommodate a varying production range. In order to resolve this conflict, increasing the adaptability of the manufacturing process will be required; however, this often causes a bigger challenge as the manufacturing resources will need to be changed.
- The conflict line between quality and speed illustrates that it is harder to improve the quality of a product rather than increase the speed, understandably. Following this, it is easier to manufacture a product quickly than produce a good quality product. By good manufacturing and process planning both goals are capable of being efficiently compatible with one another.
- The final conflict line between economy and speed illustrates that they both are interdependent on one another and that both can be enhanced simultaneously. For example, when developing a product, good process planning will reduce the actual setup time causing the setup cost to decrease. This will reduce the lead and manufacturing time of the process which, in high production, reduces the inventory costs. In terms of relationship, these two goals are positively correlated.

2.8 Developing Resource Efficient Manufacturing Process Chains

With regards to the value stream method literature mentioned above, in order to create an optimised resource efficient manufacturing process, the most important underlying aspect of designing a process is to avoid waste, thus more or less focusing on cost reduction or more formally, economic efficiency. With regards to the avoidance of waste, a simple analogy of how to improve this feat will be to eliminate or reduce all non-value adding processes and focus on the value adding ones. Due to the fact that most technical issues such as production quantities or change over times are considered as a waste, the value stream method states that the main source of waste arises from uneven production. Uneven production can lead to an overburdening of personnel and machines, resulting in possible safety hazards and reliability of the quality output. It can also cause an under-load causing idle times within the manufacturing process [10].

According to Hitoshi Takeda, there are seven types of waste that occur in production. The wastes are namely:

1. Overproduction



2. Stockpiling
3. Conveyance
4. Rejections and Defects
5. Motion
6. Processing Procedures
7. Waiting Time

2.8.1 Overproduction

Overproduction refers to producing more than what the market demands. When evaluating the term from a manufacturing context, it refers to producing components with a higher yield than what was initially required or manufacturing more components than what was necessary. Instances as such can be caused by poor communication on the manufacturing floor and process planning or by production chains that have been poorly balanced with cycle times of the process. That being said, the value stream method states that not only must a large amount of focus and decision be on what to produce a part, but also on when not to produce a part [10].

2.8.2 Stockpiling

Stockpiling waste materializes in the finished goods, raw materials and semi-finished goods inventories. Excessive inventory can often have large negative effects on the resource efficiency of process chains as it is able to hide production problems and act as a yield to eliminating the problems [10]. For example, if something does happen to go wrong, there is always a backup lying somewhere around, giving manufacturers a sense of security to their work. Inventories and stockpiling allow production to look like it is running smoothly even though it is running unevenly. However, as shown in the famous ‘ship of production’ illustration in Figure 14, inventory hides all the costly wastes associated with production.

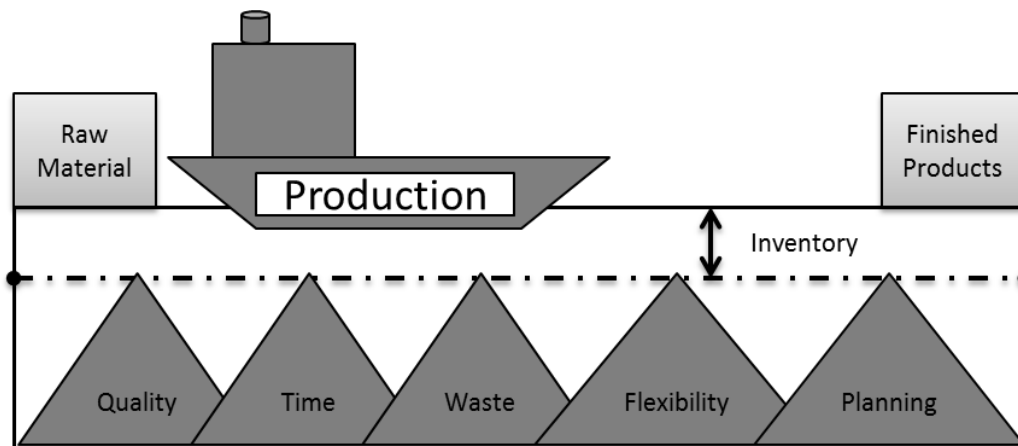


Figure 14: Ship of Production- an illustration of stockpiling (adapted from [10])



As seen in the figure, while stockpiling exists, the ship is able to flow freely over the mountain peaks (work floor problems) and only through constant stock reduction will the mountain peaks be made visible to the ship. That being said, when they are visible it puts the ship out of production. This essentially needs to happen so that constant improvements and optimisations are able to be made resulting in highly resource efficient and waste free processes [10].

2.8.3 Conveyance

The logistics of transport to and from storage locations and the transfer of goods is a major waste producer. Components and parts are often just delivered and dropped randomly at various storage locations that are not defined. Conveyance is easily avoidable through planning and arrangement of storage spaces for manufactured parts [10].

2.8.4 Rejections and Defects

When analysing rejections or defects from a value stream perspective, when a manufacturing fault occurs during the process it destroys the value of previous processes. If the fault is not specifically identified and examined immediately, normal processes that were previously value adding will be deemed as waste or require a rework on the component/components being manufactured [10]. Therefore part of the value stream method is the identification and correction of faults so that no further non value adding processes are present. If this is performed fittingly, perfect resource efficient parts will be able to be produced. Following this, quality control can be seen as a waste essentially meaning that quality control should try to be minimised. Technically speaking, the process will never be flawless from the beginning, thus testing quality is necessary.

2.8.5 Motion

Poor ergonomics and ancillary activities causes motion waste. Inefficient workplace design with poor layout designs of the machines and tools needing to be frequently used [10]. Motion waste comes from a complete ergonomic perspective in which manufacturing efficiency is decreased due to cases such as constantly picking up and putting down parts, re-gripping parts or walking distances around the work floor that are unnecessarily too long.

2.8.6 Processing Procedures

Processing waste directly results from a poor manufacturing layout in terms of the positions of the machines. This technical quality often results in the following; machine cuttings have to be manually removed by hand, reference/workplace surfaces needed to be cleaned constantly, parts and machines needing to be fixed manually during a process, machines needing to be triggered manually or buttons pressed, or the machines and parts



constantly needing manual adjustments for different part production [10]. When looking from a broader perspective, outdated technology may well be the main reason for processing waste.

2.8.7 Waiting Time

Waiting time waste is caused mainly by two reasons in a production process. Limited amounts of material for example, may show that there are problems in the production control. For this problem, it is beneficial that substitute activities during material shortages be prevented in order to not camouflage the waste.

The second reason is due to the fact that operators exist who simply monitor an automatic manufacturing process. In order to alleviate this waste, a simple change can be made so that one operator is responsible for a number of workplaces, for example, production lines and machine handling [10].

2.9 Process Technology of Additive Manufacturing

Additive Manufacturing or more commonly referred to as AM falls heavily into the Rapid Prototyping field. Traditionally, Rapid Prototyping was used to simply create parts for observation purposes, but in the modern era, Rapid prototyping has evolved into the manufacturing and development of functional and usable parts and products [77]. These technologies are placed in the Additive Manufacturing category. Unlike the initial subtractive process in order to create a part where a large piece of material is cut and machined into the desired product, metal powder based additive manufacturing technologies use a technique in which a material is added layer by layer until the desired part [78]. This layer by layer process gives users the ability to design and develop objects/products that have complex and unusual geometries, giving the designer/user a large amount of possibilities and freedom, unlike the traditional method. Additive manufacturing is especially useful in both the biomedical and aerospace industries due to the production of intricate and unusual parts [79]. AM performs well economically when compared with the conventional method as there is limited amounts of waste product due to there being no 'off cuttings'. There is an estimate that there is 35% cost reduction when using the additive manufacturing process of developing a femoral stem as opposed to the conventional method. Similarly, there is also a calculation that states when an aerospace bracket is produced using AM technologies, the cost of the production process is decreased by 50% [80].

There are six basic steps to almost all additive manufacturing technologies process chains and these are presented in the following chapter, together with the explanations of each of the different steps. To understand the different underlying concepts and paradigms of AM technologies, it is obligatory that an overview be presented of the different technologies that are used in order to fuse the metal powders together [81]. Due to the amount of various additive manufacturing technologies currently available on the market, the research has been



streamlined to focus on technologies involved in the production of components utilised in this research study. The technologies that are focused upon are the ones which cure and fuse together the metal powder, layer by layer, to a specific thickness as given by the geometry of a 3D CAD input file [82].

2.9.1 Basic Process Chain for Additive Manufacturing

There are many different ways in which one can produce a product or part via additive manufacturing. These additive manufacturing process chains all show specific individualities with regards to their machining processes that respectively differentiate them from one another. This enables one to develop a ‘generic’ process chain for the additive manufacturing which one can work off to change certain steps within the chain for comparison of efficiency.

Each AM process chain mainly consists of five steps:

1. Part Design (CAD)
2. STL file preparation and verification
3. Machine Setup
4. Construction of the Part
5. Post Processing
6. Quality Control

As seen by the figure below, 3D CAD modelling has been included in the AM process chain. Although it is considered not be part of the AM process, it has been included in the process chain below due to the fact that all additive manufacturing processes begin with the design of the CAD model and is thus seen as the input to the process chain. Essentially speaking, output quality of the process chain is directly linked to the input quality.



Figure 15: Generic Process Chain for Additive Manufacturing

With regards to the CAD modelling step in the process chain, currently all commercialised CAD packages are able to export the part, designed in CAD, to STL file format. That being said, not all CAD software packages are



able to produce the same quality and accuracy of STL files. This is thus important to take into consideration when choosing a software package to use [83].

STL files consist of a mesh of triangles that effectively gives the geometry of the part. The STL file can either be exported in an ASCII format or a binary format which contains the vertices of each triangle found in the file which thus gives the 3D CAD model. The figure below depicts the concept of the conversion of CAD to STL.

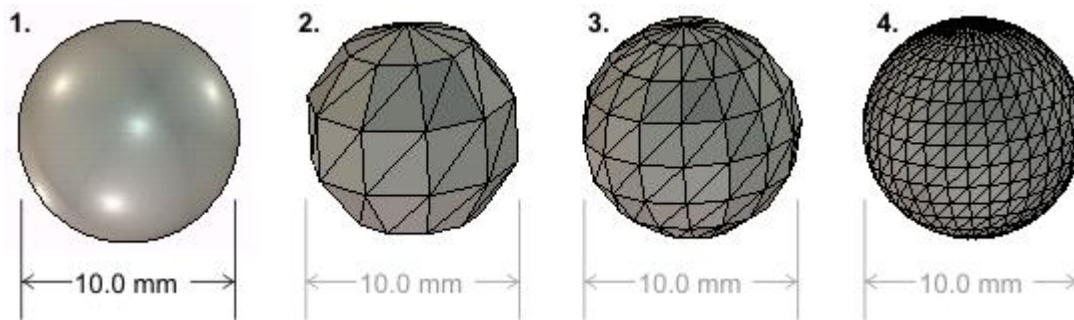


Figure 16: CAD Models to STL File (adapted from [97])

Following the generation of the CAD model to the STL file, verification and repair of the file needs to take place. This ensures that all defects that were present in the file are removed. The most common defects of an STL file are near flat triangles, overlapping triangles and non-coincident triangles. A valid STL file is one which the two vertices of the triangles are shared by the adjacent triangles and surface normal face in an outward direction. Even though there are some software packages on the market that have refining and repairing toolkits, it is still advisable to review the file in order to ensure there are no reworks from them AM process.

The next characteristic in the process chain of AM is the machine setup. This step contains a number of sub-steps in order to be completed, the first being part orientation. As previously mentioned, the AM goes about a layer-by-layer process thus entailing a phenomenon known as ‘stair-stepping’. If the part being developed is completely horizontal or vertical however, this phenomenon doesn’t exist. Stair-Stepping can be reduced by reducing the layer thickness in the process; nonetheless, this increases build time.

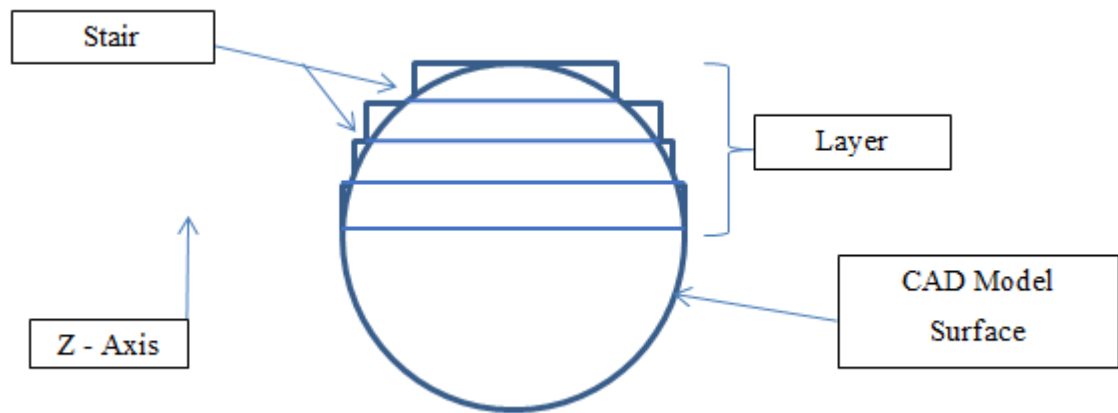


Figure 17: Stair Stepping Effect (adapted from [82])

An important aspect to keep in mind while using AM technologies is whether or not support structures are needed during the process. These support structures serve as two functions, one being they connect the base plate to the part and the other being they keep the overhanging geometries in place. The support structures can be placed within the parts features to make sure there is no movement during the AM process and thus provide high accuracy. After the process is complete, the support structures need to be removed. This is sometimes not a simple process and they either have to be chiselled away, removed manually or machined.

The next generic step is the construction of the part. Firstly the number of layers that are going to be needed in the production of the part needs to be decided. This is all dependant on the range of the layer thickness that will be used with the AM technology. Each layer contains the cross sectional two dimensional geometry of a specific height of the part. Essentially, these geometries are the X and Y tool paths which the technology takes to produce the part. As mentioned previously, the stair stepping effect must be decided on factors such as part integrity or build time.

From here the part placement can be set on the build plate together with the creation of the build file. Due to the fact that the process parameters of AM systems are usually default, one needs to take into consideration the parameters used for the process of the production [82] [83] [84].

Once the part is complete, it can be removed from the machine together with the support structures. Post processing operations such as cleaning, bronze or wax infiltration or sandblasting can be performed to ensure the functionality of the part is present for its intended use.



2.9.2 Additive Manufacturing Technologies for Titanium Components

2.9.2.1 Stereolithography

Stereolithography, more commonly referred to as SLA, is an AM process that is liquid based and argued to be one of the first build blocks towards an additive paradigm [85]. During the SLA process, a stationary UV (ultraviolet) laser is used to scan and cure over a photosensitive polymeric resin. The laser's path is determined by scanning mirrors regarding a 2D, X-Y plane [82]. The energy given from the laser penetrates through the photopolymer and causes the resin to solidify. Figure 18 below shows.

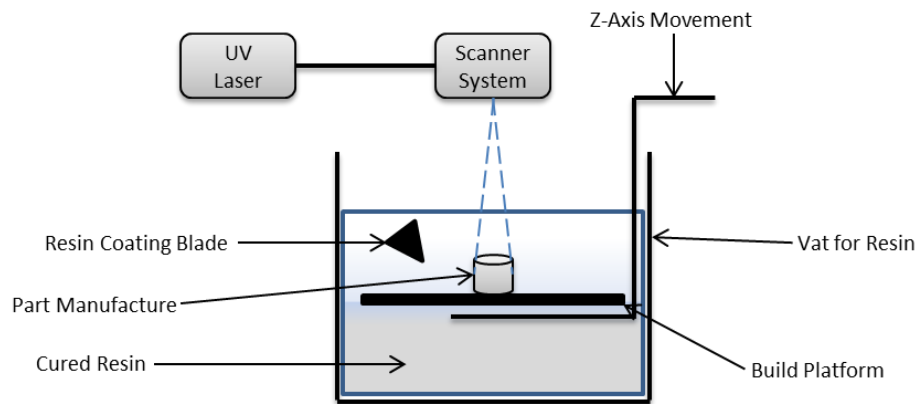


Figure 18: Illustration of the SLA process (adapted from [86])

Once the cross section of the part has been fully scanned by the laser and the resin has cured respectively, the build platform is lowered in the Z-direction into the resin by a preset layer thickness. This thickness is usually $100\mu\text{m}$ [85]. A coating blade is then used to make sure that a fresh, new even layer of resin is dispersed onto the build platform. The new cross section is taken from the CAD model and scanned and cured. This process is continued until the entire component is complete. Post processing of the parts usually involves placing them inside UV or a thermal oven in order to ensure the resin is cured.

2.9.2.2 3D Printing

3D or three dimensional printing originated through research directed at Massachusetts Institute of Technology (MIT) in the 1990's [87]. The way in which 3D printing works is through drop on demand jetting technology. This technology produces droplets of binder fluid that are selectively dropped, layer by layer onto a powder bed. The binder fluid then solidifies developing a XY cross sectional geometry of the given CAD model. An illustration of the process can be seen in Figure 19.

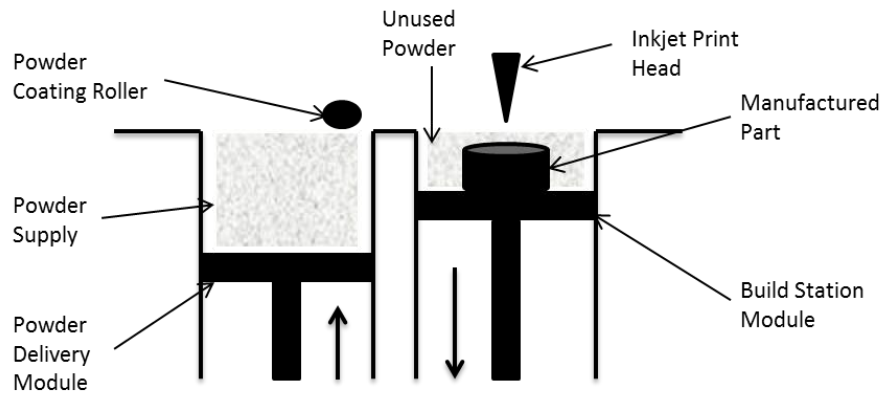


Figure 19: Illustration of the 3D printing process (adapted from [85])

At the start of the process, the build station is lowered to the layer thickness of the print which is usually in the range of 0.080 – 0.250mm thick [88]. Powder is supplied by the powder delivery module and spread evenly over the build by a coating roller. An inkjet print head then drops the binder fluid onto the powder layer by layer (as mentioned above). This process is repeated until the component being manufactured is complete. Once the process is finished, the binder fluid is given time to harden and dry before it can be extracted.

2.9.2.3 Selective Laser Sintering

SLS, also known as Selective Laser Sintering, is a process similar to that of 3D printing where it produces 3D components through a layer by layer fashion (see Figure 20 for process illustration). In order for this process to perform, a CO₂ Carbon Dioxide laser supplies thermal energy within a highly controlled environment to powder particles in order to fuse them together. A system of scanning mirrors inside the technology control the focus points of the laser and guides the laser to the powder bed to fuse together the 2D profile layer. Like the 3D process, the build station is lowered in accordance to the layer thickness of the build (usually between 0.02mm and 0.15mm) [89]. The new powder is gathered and a coater roller distributes the powder out evenly so that the next profile can be scanned, layer by layer. This process continues until the CAD model used is developed. Inside the build chamber, the powder is preheated to a temperature just below the sintering temperature of the material. This prevents different thermal gradients between sintered powder particles and non-sintered particles. The non-sintered particles act as supports for the component. On completion, the build station rises. Before the part can be removed, the chamber must first cool down. Metal parts are however not completely dense after the process and thus post processing processes such as burning away the polymer coating in a furnace is performed.

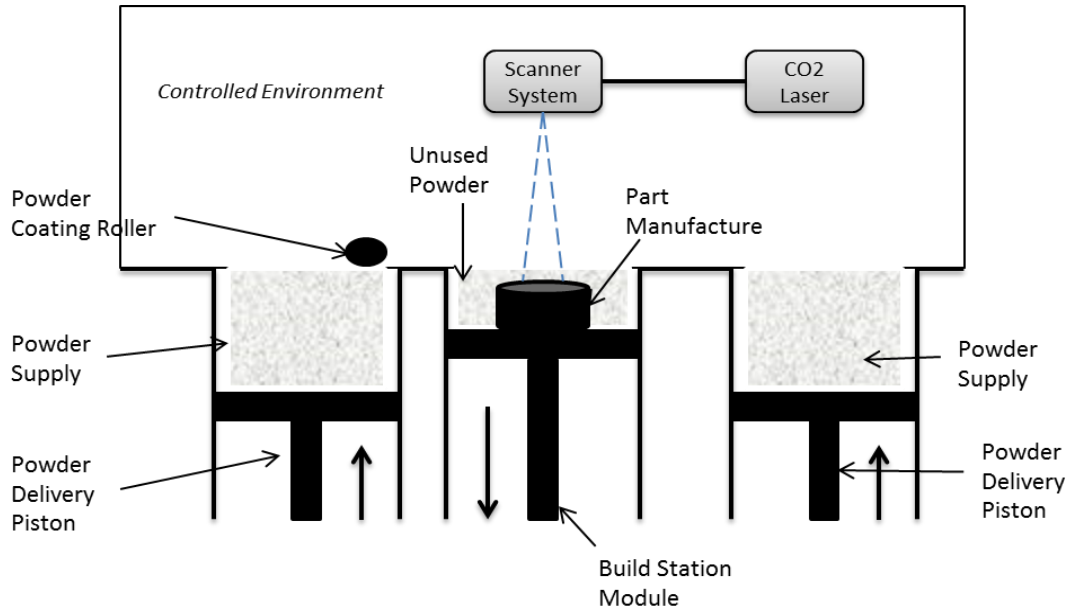


Figure 20: Illustration of SLS Process (adapted from [85])

2.9.2.4 Selective Laser Melting

Selective laser melting, more commonly referred to as SLM, is a process that produces metallically diverse parts via freeform fabrication. Like the SLS process, the SLM uses a fibre laser instead of a CO₂ laser. High energy beams are used in this process where they scan over a bed of powder in a layer by layer process [90]. CAD (Computer Aided Design) cross sectional data files are used to programme the SLM scanner so that it knows in which direction to cross over the powder bed. The files are uploaded to the machine so that the various process parameters can be set. During construction of the part, the metallic powders combine to form the shape. The shape, after this process, is often very close to full density, up to $99.81 \pm 0.1\%$ as per studies, and rarely has to be manipulated [91]. The bed of the SLM machine is lowered after every cross section is complete. The usual displacement is 30-70 μm [92]. From here, the SLM machine places a new fresh layer of powder over the bed for the scanner to scan. This lowering, covering and scanning process continues until the part is produced. The process can be seen in the depicted Figure 21 below [93].

The SLM machine needs to be in an environment that is controlled and inert in order to reduce the risk of metal oxidation. In order to reach this specific environment, the building chamber needs to be flooded with either Argon or Nitrogen gas. The type of gas used depends on which type of metal alloy is used for production. These gasses force out the Oxygen content so that a unit of 0.1% and below is achieved [94].



Upon completion of the part, the support structures need to be removed in order to be extracted. These structures are either machined or chiselled off manually depending on the situation. From here, relying on the requirements of the part, further machining, may be necessary in order to smooth the roughness of the chiselled/machined surface [95] [96].

When compared to other manufacturing technologies, the SLM machine benefits when parts with complex geometries are needed to be produced. Excess and left over powder can also be recycled and used in for future productions.

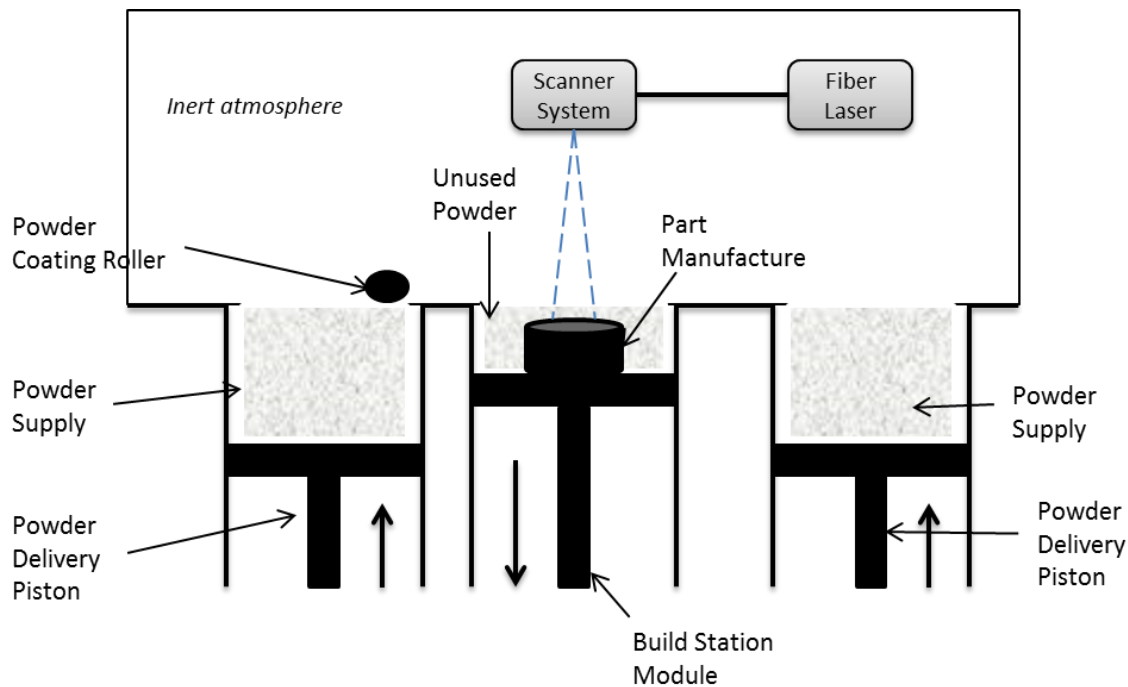


Figure 21: Illustration of the SLM Process (adapted from [93])

2.9.2.5 Casting

There are two types of metal casting namely expendable mould casting and permanent mould casting. Depending on the type of mould that is going to be used, the manufacturer will decide which casting process he will choose in order to produce the part [97].

Sand casting is the most popular type of expendable mould casting and is the amongst the cheapest types of casting due to the fact that it is able to produce smaller batches than other castings. It involves sacrificing the mould in order to retrieve the product. Molten metal is poured into a sand laid mould. This sand is understandably not the sand found in an average garden, but a specific type of sand that contains both minerals, SiO_2 (Silica), water and clay. If a stronger mould is required, bonding material can be added to the mixture.



Once the sand is placed inside the mould, two halves of the mould are clamped together in order for the casting process to begin. The metal is then poured into the mould. From here the metal then cools and solidifies until it is able to be removed from the cast. Post process operations can be performed if needed be [97].

Permanent mould casting mainly uses metals to produce a part. The process combines reusable moulds over and over again in order to create the necessary part. The most industrial way of processing a part with regards to this type of casting is by using gravity to fill the mould. This gravity mould process is widely used in order to create metal parts that have a hollow shape. Vacuum and gas pressure however may also be used to create these shapes.

Looking at the permanent moulding process from economical front, the cost to produce a single part will be more expensive than the sand casting process, that being said however, this process is mainly used when the manufacturer knows that the part will be used again. When looking at it in a 'long-run' sense, it will be the more economical option [97].

2.9.2.6 Electron Beam Melting

Electron Beam Melting utilises an electron gun that powers a highly powered electron beam. This is performed by heating tungsten filament to a temperature higher than 2500°C, which in turn emits electrons, and creating a higher voltage difference within the assembly in order to accelerate the electrons [98]. The voltage difference is created by operating the electron gun at a voltage of 60kV. Deflection coils control and position the electron beams which melt the powder on that table so that creation of the part can take place. EBM is also a layer by layer process like the SLM with thickness of the layers varying between 0.05-0.2 mm [99]. The EBM machine process can be seen in figure 8 below.

The metal powder is fused together from heat generation caused by the electrons losing kinetic energy as they fall onto the powder. As previously mentioned, similarly to the SLM process, once the bed of powder has been completely scanned, the table bed the powder is on then lowers so that a new layer of powder can be deposited. A powder coating blade then moves across the entire bed to ensure the powder is evenly spread. The process previously described repeats itself until the part is complete [98].

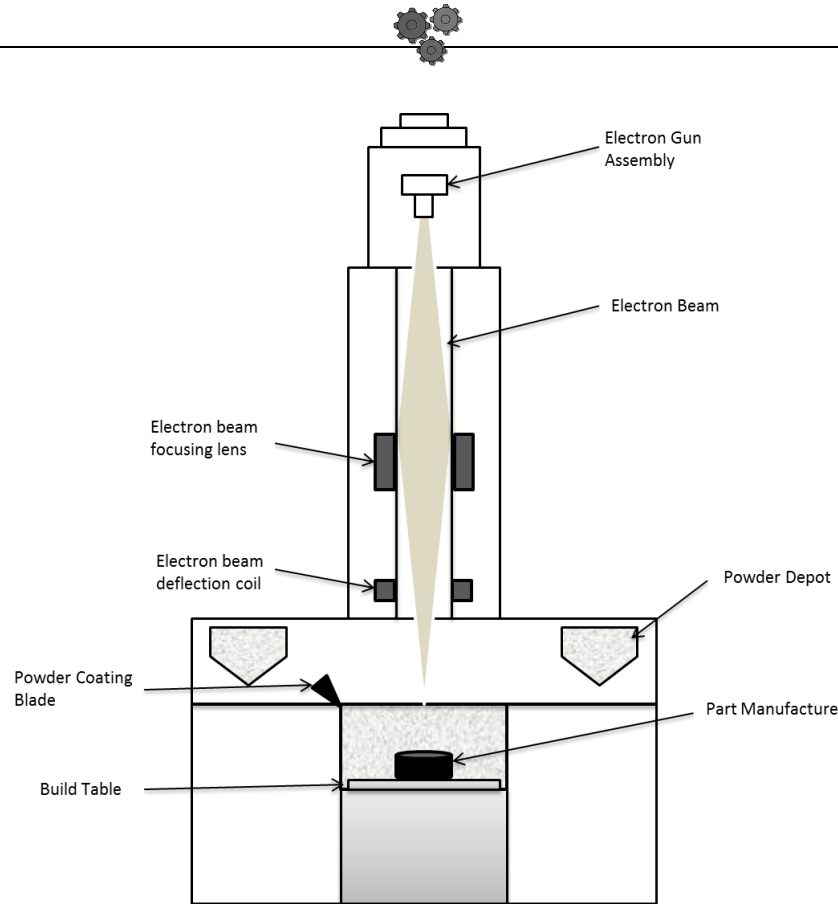


Figure 22: Illustration of the EBM Process (adapted from [100])

2.10 Subtractive Manufacturing

Subtractive manufacturing is a prototyping process in which components are developed by removing material from a solid billet [101]. This form of manufacturing can be performed by simply manually cutting away the specific material or by using known machining processes, for example, drilling, milling, turning or lathing, until the required part is complete [102]. By performing these processes, it allows manufacturer the ability to manufacture both large and small volumes and manufacture components with specific finishes or components with specific mechanical properties. Subtractive machines such as the CNC are also able to run 24 hours a day, 365 days a year continually without have the need to be switched off [103].

Subtractive manufacturing is typically performed by a CNC machine and works with metals and resins such as Lexan Lucite, Nylon, Aluminium, Acrylic, Teflon, Acetyl Copolymer and for this study Titanium [102].

2.10.1 Basic Process Chains for Subtractive Manufacturing

There are many different ways in which one can produce a product or part via subtractive manufacturing. Much like the additive manufacturing technique, the process involves design a part through CAD so that it can essentially be uploaded to the CNC machine in order to begin the manufacturing process.



Each subtractive manufacturing technology and process chain consists of mainly 5 steps:

1. Part Design (CAD)
2. Detailing (CADD)
3. Path Planning (CAM)
4. Billet Clamping
5. Billet Machining (roughing, milling, turning)
6. Finishing and Cleaning of the Part

As seen in Figure 23 below, a typical illustration of the basic process chain is shown. As seen from the steps, a CAD design of the part to be manufactured is first needed to be produced. Upon completion of the CAD design, the specifications for the part are known and the ‘to be’ manufactured part can be viewed as a 3D model [104]. From here, the part goes through detailing where the manufacturing requirements for the specific part can be determined and the partial geometry of the part. The path planning for the manufacture gives manufacturers the ability the ability to calculate and evaluate the tool paths of the manufacture. Due to the fact that the manufacturing environment is ever increasingly complex, CAM software has become a necessity of late giving users the ability optimise the tool axis tilt for high speed rates of five axis machining, prolonging tool life together with better surface finishing and simply optimising non-cutting procedures such as the probing motions of the CNC machines.



Figure 23: Basic Subtractive Manufacturing Process Chain

Once the streamlined tools paths have been optimised, the billet intended for manufacturing can be placed and clamped in a position on the work piece so that it can be machined to completion. Once the billet is fully machined, a near-net shape part is produced and can be completed through the finishing and the cleaning operations. The finishing and cleaning operations can include magnetic polishing, ultrasonic polishing, sandblasting, lapping, filing, sanding and rumbling and tumbling [105].

2.10.2 Subtractive Manufacturing Technologies for Titanium Components

2.10.2.1 CNC Machining

CNC Machining, also known as Computer Numerical Control Machining, is a process whereby a component is developed by machine tools controlled by a programmed computer [106]. Tools such as grinders, mills, lathes and routers are able to be controlled by these computer systems. After programming the toolpath, human



attention to the development is not as necessary as with other manufacturing techniques. The CNC machine follows this toolpath controlled by data known as alphanumeric data [97]. Once the CNC machine is programmed with this data, it is able to perform operations such as drilling, profile milling, sinking operations and surface contouring. These different capabilities however depend on the amount of axes the CNC machine contains. For freeform surfaces such as aerospace and medical components, the most commonly used CNC machines are the 3-axis and 5-axis machine [107].

Due to the fact that the CNC machine is controlled by a computer programme, components with complex geometries are able to be machined. Complexity however increases due to the selection and changing of the automatic tool. Even though this proves to be a disadvantage of using the CNC machine, the CNC machine is able to produce more than one component from a solid billet. This reduces the cost of machining exponentially [108].

2.10.2.2 Laser Beam Machining

Laser Beam Machining, also known as LBM, utilises a lasers light energy in order develop a part. The laser respectively removes material from a solid billet by a process known as ablation and vaporization. The laser light beam is optically concentrated and released in pulses in order for the concentrated energy to impulse against the solid billet being worked. These impulses on the surface of the material cause melting of the material together with evaporation. Once the process starts, the thermal energy created by the laser melts away the material, thus forming the component required. Laser Beam Machining is considered not to be an effective strategy for mass production, due to the cost and thus producing single components is more effective. For operations such as cutting slots, drilling, marking components and scribing, LBM is the most effective due to its accuracy. Hole diameters as smalls as 0.025mm can be drilled [97].

2.10.2.3 Electrical Discharge Wire Cutting

EDWC is a process whereby a small diameter is used to cut a piece of solid. This wire essentially works as the electrode of the process and is able to cut the solid billet into the required component by guiding the solid passed the wire on a chosen guided cutting path. Like the CNC machine, the EDWC is programmed by numerical control in order to maintain its motion throughout the process.

During the operating process, the wire used for the cutting is constantly changed so that a new fresh electrode with a constant diameter is always used. This ‘changing’ process is done by the wire moving from the supply spool to the take up spool. This constant diameter of the cutting wire will ensure that the kerfs of the wire are always of the same width and nature. Depending on the customer requirements, the kerf widths can range from a



diameter of 0.076mm to a diameter of 0.3mm. This however is not the actual diameter of each kerf. With each cut from the wire, an overcut occurs which adds on between 0.02mm and 0.05mm to each kerf. The main advantage of the EDWC manufacturing technique is that there are no cutting forces between the component and the wire allowing for extremely precise geometries to be cut. This process only works with materials that are able to conduct electricity and the wire cutters performance is not affected by the toughness or the hardness of the material being operated on [97].

2.10.2.4 Electrical Discharge Machining

Electrical Discharge Machining, also known as EDM, is a process whereby a component is manufactured by the removal of material via continuous electrical discharges. A more basic term for these electric discharges is 'sparks'. As in the case of Laser Beam Machining, the discharges are able to melt away the material being operated due to the extreme confided temperatures produced by the discharges. The final finished component is developed by a formed electrode tool. The discharges needed for the process occurs between the component being operated on and the formed electrode tool. The work piece together with the tool are connected to a pulsating power supply which essentially creates the discharges. A fluid known as dielectric fluid, creates the tool path by ionising the gap between the work piece and the tool. As melting of the work piece commences, the removed material is taken away the excess flowing dielectric. As soon as a section of the work piece is removed, the distance between the electrode tool and the work piece increases. As soon as this distance increases, the discharges stop at that specific spot until the surrounding area is levelled to the same height.

2.10.3 Forming

Metal Forming is a process whereby the part being developed is plastically deformed into the desired geometry of the shape. Forming is defined as an extremely general and broad term in a sense that it involves a range of manufacturing processes. In order to deform a metal essentially, a force should be applied that is stronger than the yield strength of the material, in this case Titanium. If a low amount of force is applied to the metal, it will simply change its geometry slightly, understandably in the direction of the corresponding force. Basically speaking, the metal material will bend, compress or stretch a small amount with regards to the amount of force applied in that direction to the material. Once released, the material will return to its original position. This is known as elastic deformation [109].

In plastic deformation, the change of the geometry of the material is no longer directly proportional to the amount of stress induced, and the changes remain after the stress is released.

The different metal forming processes are grouped into two main categories, namely the bulk deformation and the sheet metal working.



With regards to bulk deformation there are four processes involved; rolling, drawing, extrusion and forging. When looking at sheet metal working, there are three processes involved; shearing, deep drawing and bending [109].

2.10.4 Joining

Sometimes, components and parts are too big to be made by individual manufacturing processes, for example a three dimensional hollow structural member. This where joining is utilised in the manufacturing industry. Joining operations in the manufacturing industry involve welding, soldering, brazing, mechanical assembly and adhesive bonding. With complex geometries that other manufacturing technologies are unable to produce, joining becomes an economical method of manufacture and can allow for disassembly of parts and varying functionality of the product, for example, inserts of carbide in tool steels [110].

2.10.5 Combining Additive and Subtractive Manufacturing

Over the past few years, focus has shifted on a global manufacturing scale for manufacturers to concentrate process chains as a whole instead of trying to optimise solely production rates or cutting parameters [111]. That being said, resource efficiency of the entire process is now taken into account resulting in the production processes being governed by high performance processes together with hybrid processes and near-net-shape implementation. These different strategies are directed towards to reducing elements of the production line such as costs, emissions, manufacturing/cycle time and material waste, all the while increasing elements such as productivity, performance and profitability [112]. Currently, there is major encouragement for industry and researchers to manufacture products using a more efficient way in the form of hybrid manufacturing. In literature studies, there are different meanings and definitions for the conned term ‘Hybrid’ [113]. The 2014 CIRP workgroup gave the following definition for hybrid processes: “Hybrid manufacturing processes are based on the simultaneous and controlled interaction of process mechanisms and/or energy sources/tools having a significant effect on the process performance.” After research however it is also noted that some academics refer to hybrid processes as processes combining both in series and simultaneously [114] [115].

Generally speaking, manufacturing technologies are able to be split between five main groups, namely additive, transformative or forming, subtractive dividing and joining [116]. That being said, researchers, together with manufacturers, have taken serious consideration to the conned term ‘Hybrid Manufacturing’ and further classified the manufacturing technologies into seven groups [115]. The further classification of the manufacturing technologies are as follows:

- Additive
- Subtractive/Cutting



- Joining and Subtractive
- Additive and Subtractive
- Additive and Transformative

The current research of this study incorporates the various manufacturing technologies mentioned above into the manufacturing of Titanium components.

With regards to previous research, when combining additive and subtractive manufacturing processes, a biased additive strategy is commonly used in order to develop the near-net shape part, due to the fact that additive manufacturing is currently the most utilised manufacturing technology nowadays. This additively formed part is then further machined to the final desired shape using a subtractive process [115]. That being said, other process chains regarding combining the subtractive and additive processes have been researched which will be discussed in the following chapter.

A schematic representation of the costs involved using the two different manufacturing technologies can be seen below. This figure however depends on the batch size of production and the size of the part being produced as, for obvious reasons, costs for additive processes increase as the volume of the part increases and vice versa for the subtractive process, as volume of the part increases using a subtractive process, less material is needed to be removed [117].

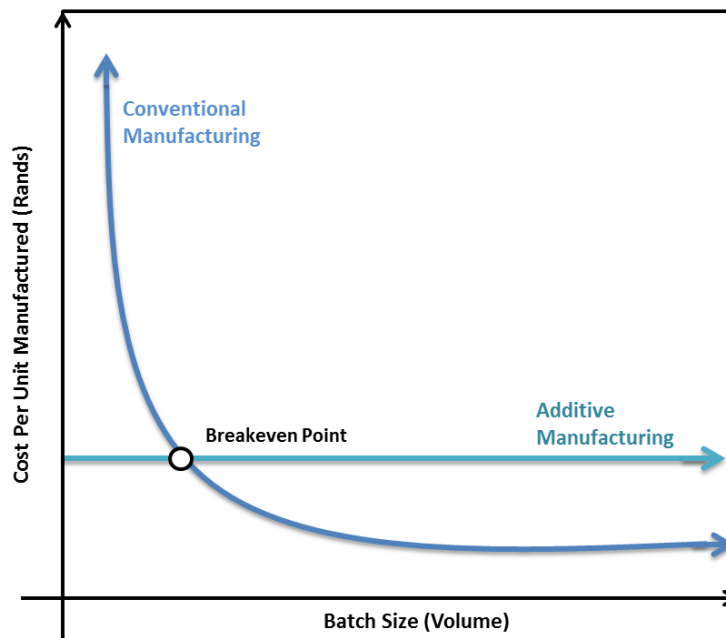


Figure 24: Schematic Representation of the Costs Involved using Additive and Subtractive Processes (adapted from [48])



2.10.5.1 Researched Additive and Subtractive Combinations

In 2010, Karunkaran investigated a hybrid manufacturing technology using a system of layer-by-layer production of the near-net shape through weld deposition combine with CNC milling for the finish machining of the component on a retrofitted workstation. After the evaluation of the combine process chains, they calculated that there was much as 42% time saved of the process, less material was utilised and 28% was saved on manufacturing cost when compared to the purely CNC route respectively [118].

In 2006, Song and Park combined two different approaches to the hybrid manufacturing technique by using CNC milling and arc welding. The first approach saw two metal arc welding guns that were used to place different materials on the boundary and the inside of a layer. The second approach that was used saw arc welding guns develop the outline of the component needing to be manufactured followed by the filling of the previously mentioned outline using low melt metal alloys. Once each of the different approaches were complete, CNC machining was then performed for final finishing of the product [119]. In 2011, Suryakara examined the process of combining face milling with inert gas welding. This process was deemed unsuccessful and time consuming as the combine processes were applied on every layer, resulting in a resource efficient loss [120].

Another process combination that was tested was that of using abrasive polishing as a subtractive process combined with electroforming as the additive. Nodules were developed during the electroforming process hence the reason abrasive polishing was required. Although it was a time consuming process, the mechanical properties of the final product were good with R_a (surface roughness) as low as $0.012\mu\text{m}$ [121]. Other combinations that have been evaluated are ones such as manufacturing process tested by Kelkar and Koc in which free form objects are developed by a combination of rapid mould tooling using a layer-by-layer process together with multi-axis machining. Once the part is moulded using the additive process, finishing and final operations are performed with the multi-axis machine. Other authors have too investigated many other approaches using laser cladding for example, as an additive approach with final finishing operations of a CNC milling machine [122]. As previously mentioned, most combinations of additive and subtractive machining result in the production of the part using the additive strategy and the finishing operations using the subtractive strategy. Combining these two technologies to produce a part deems to be a viable solution in order to improve the resource efficiency of the production process as the literature based reviews all lead to the common theme of reduction in material waste, cost and time [123].



3. *Conceptual Framework Development*

The following chapter discusses the different techniques that will be used to develop and evaluate the process chains that will be investigated in this research. The evaluation technique will be considered with regards to the three benchmark components that will be investigated in this study.

A general framework has been designed in order to follow a structure in the development and evaluation of resource efficient process chains.

3.1 *Development of a Conceptual Framework through a Systematic Approach*

One of the main challenges in developing a framework and model in order to investigate the resource efficiency of different process chains is trying to find the optimal solution to the problem in the most generic way, so that the developed framework does not restrict any type of manufacturer wanting to know the best approach to go about manufacturing what is required. Another major aspect to consider when developing such a framework is its complexity. When using the proposed framework, it should allow for easy use and practical implementation. A conceptual framework is defined as type of process used for the mapping or illustration of theoretical threads in order to develop a diagrammatic representation of inter-relatedness [124]. That being said, an initial conceptual framework was developed in order to identify the basic necessities for a evaluating and investigating a manufacturing process chain and to also develop a specific structure for evaluation so that further refinement and development on the framework can be performed. In order to identify the elements required in the framework, gained knowledge from the literature study was used where the key elements affecting the resource efficiency of process chains were identified.

The basic conceptual framework developed will be used as a building block in order to identify the various complex elements needed to be considered when designing a process chain. Each phase of the framework is used to focus on different features of a manufacturing process chain in order to break down the chain into its primary processing units. Using a methodical approach, the framework was constructed through different stages in order to incorporate the various resource efficient elements associated with Titanium process chain manufacturing. In order to develop the framework, the basic process chain for manufacturing a Titanium component was analysed. The process chain was then divided and categorized as a function of four key factors as shown in the Figure below:

- Part Design
- Developing and Integrating Process Chains
- Identifying and Evaluating the Factors Affecting Process Chains



- Excel Based File Validation

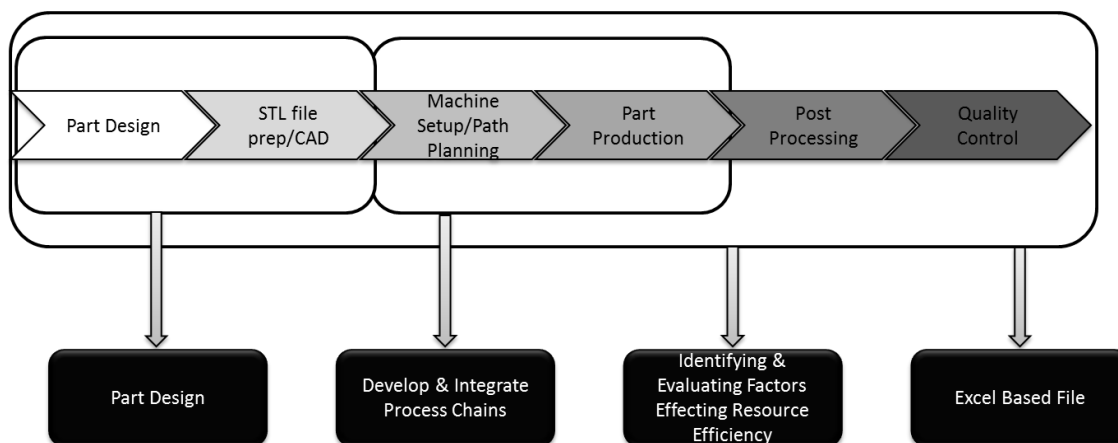


Figure 25: Illustration of the Conceptual Framework Development

Knowing these initial framework steps, the first conceptual framework was developed in order to investigate resource efficient process chains. From the research, different factors affecting each of the distinguished categories were sub-categorized for manufacturers to follow.

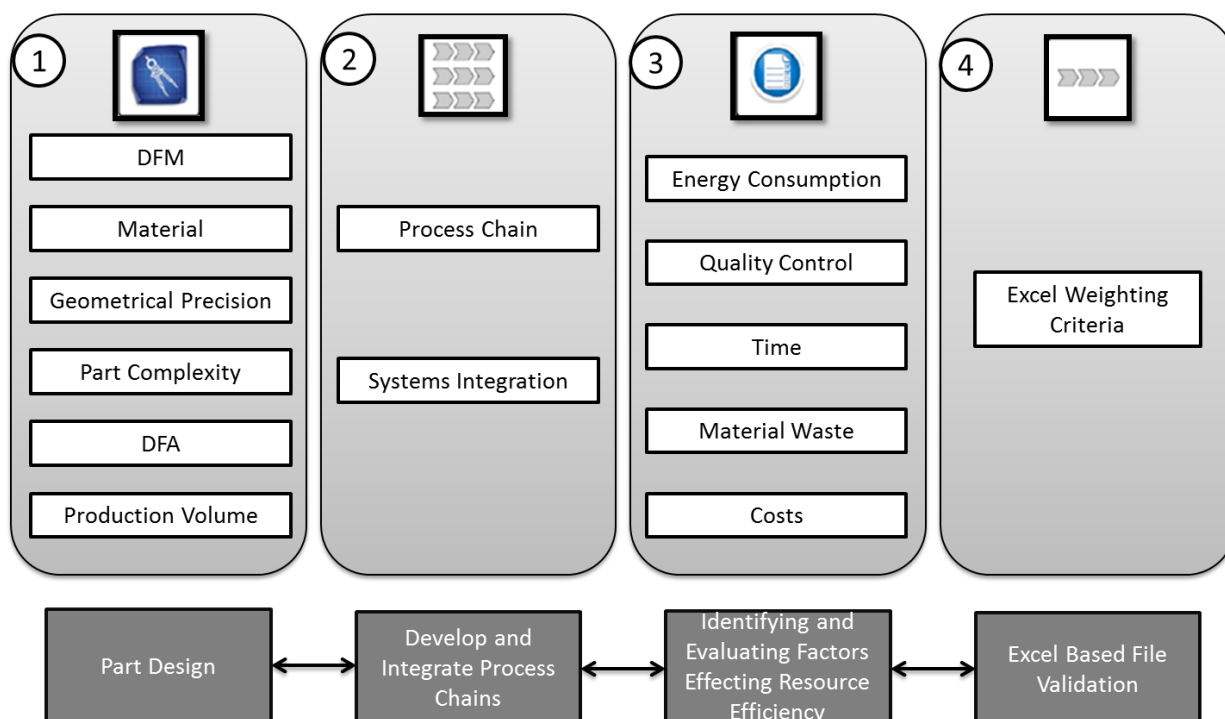


Figure 26: Developed Conceptual Framework



By iterating and refining the different phases of the conceptual model, as discussed later in this chapter, recurrent elements or shortcomings can be identified in order to isolate them into one final generic framework.

3.2 Framework Overview

As previously mentioned and as seen by Figure 26, the framework occurs in four phases in order to assist manufacturers in designing resource efficient process chains.

3.2.1 Part Design

DFM (Design for Manufacture) and DFA (Design for Assembly) basically means that manufacturers should modify the part design in order to minimise both manufacturing and assembly costs, and to remove any difficulties concerned with manufacturing. DFM specifically refers to the optimization of the manufacturing process by reducing the total part production through minimisation of the complexity of manufacturing operations and by using a primary axes and common datum [125]. DFA on the other hand refers to the optimisation of the part/system assembly by reducing product assembly cost through minimising the number of assembly operations and by determining the production volume of reach build as individual parts often bias themselves towards complex designs.

When coming from AM perspective as opposed to a traditional conventional method, both DFM and DFA have to be rethought in order to fully utilise the different functionality advantages of using AM. Essentially, DFM and DFA is directed towards the designer understanding the manufacturing processes various constraints, then designing the manufacturing process by trying to optimise and effectively reduce these constraints. AM technologies do however reduce the number of constraints and difficulties associated with DFM and DFA.

There are currently a number of guidelines manufacturers are able to follow in order to Design for Manufacturability and Assembly efficiently. The table below shows the guidelines and the effects they essentially have on the manufacturing process chain. When following these guidelines it is easy to identify that the shape complexity or part complexity, the material use (in this studies case Titanium), the geometrical precision and the production volume all form a vital part in the DFM and DFA, hence the reason they fall under the part design phase in the framework. Please see the Appendix for the guidelines for both DFA and DFM.

3.2.2 Develop and Integrate Process Chains

The next phase of the framework brings the user to the development and integration of process chains. From knowledge gained through literature and through industry experience, it is understood that each component needing to be manufactured will have a different required method of manufacturing hence the reason process



chain development and systems integration is important to consider when designing resource efficient process chains.

Currently, with regards to this research, there are many issues faced with system integration of different process chains in the South African manufacturing industry. This is due to the fact that South Africa does not have the resources to produce components in the same way as first world and developed countries. This leaves a large space open for different integration of systems to be tested in order to identify resource efficient combinations.

3.2.3 Identifying and Evaluating Factors Effecting Resource Efficiency

As mentioned in Chapter 2.5 above, key factors have been identified with regards to investigating the resource efficiency of manufacturing a Titanium component. As seen in Figure 27, a multidimensional analysis strategy of the process chain will be used in order to complete phase 4 of the framework.

For the evaluation process, a method known as multidimensional analysis will be considered. If this method is utilised, an early holistic assessment of the investigated process chain will be capable [68]. Figure 27 below shows the different perspectives that will be used in the analysis of the process chain.

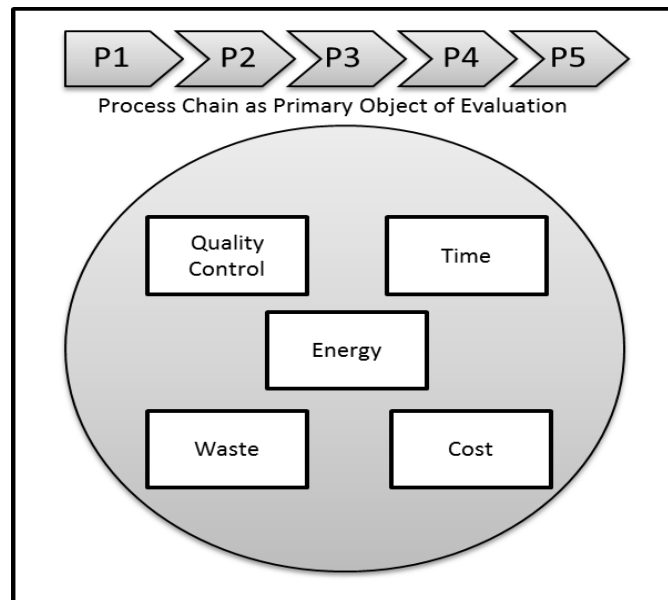


Figure 27: Multidimensional Analysis of key factors effecting resource efficiency (adapted from [68])

3.2.4 Excel Based File Validation

The final phase of the framework will be an excel file validation in which the data gathered from the various key factors of the framework will be used to determine the most resource efficient process chain. In order for the framework to determine the best process chain to develop a Titanium component, different weightings will be




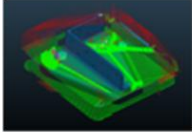
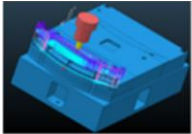
given to different process chains as, for example, some process chains are used to minimise costs while others are used to reduce manufacturing time. These different weightings will essentially validate the results of the efficiency of the processes chains, for example, a milling process has a large amount of material waste when compared to that of the Powder Metallurgy. Different weightings thus are able to validate the results for the different processes so that the results are essentially even.

3.3 Framework Validation and Iteration Methodology

In order to finalise the model to a framework sufficient for investigating the resource efficiency of manufacturing Titanium components, the framework needs to be validated through a series of three iterations. These iterations will be used through three benchmark components manufactured by the STC-LAM Labs.

Different manufacturing process chains were used for each manufactured Titanium component. By iterating the framework through these benchmarks components, specific key areas and short comings of the conceptual framework will be identified so that it can be changed and refined in order to carry out further investigations. The three benchmark components and iteration steps are illustrated in the table below.

Table 5: Validation and Iteration Summary

Part Name	Demonstrator	Application	Process Chains
1. Intelligent Implant		Medical Industry	<ul style="list-style-type: none"> • CNC Machining • SLM • Wire Cut & CNC Machining
2. Knuckle Duster		Aerospace Industry	<ul style="list-style-type: none"> • CNC Machining • SLM & CNC Machining
3. Banana Brace		Aerospace Industry	<ul style="list-style-type: none"> • CNC Machining • Forming and CNC Machining



As portrayed in Table 5, the three benchmark components being investigated is an intelligent implant used in the medical industry and a knuckle duster component and a banana brace both used in the aerospace fields. With regards to the benchmark components, each benchmark component will be investigated with regards to their manufacturing process chains. The resource efficiency of the process chains will be evaluated.

Following the intelligent implant manufacturing, four process chains will be investigated by the framework. These process chains are namely: CNC machining, SLM, Wire Cutting and CNC Machining, and SLM and CNC Machining.

Looking at the knuckle duster, the process chains that will be investigated are the CNC Machining process chain and a hybrid process of combining the CNC and SLM manufacturing technologies together.

The final evaluation will take place through the banana brace in which a traditional CNC machining will be used and then a Forming and Machining process chain will be used.



4. Validation of Conceptual Framework: Iteration 1

The following chapter presents the validation of the initial conceptual framework developed in Chapter 3. In order to investigate the resource efficiency of the different processes involved for the first iteration, a total of 3 different process chains will be evaluated through the framework. With these evaluations, a quantitative analysis will be performed for the key factors, identified from literature. Once all the key factors of the process chains have been quantified, a qualitative evaluation of the conceptual framework is performed. This qualitative and quantitative approach will also be used of for the validation of the conceptual framework presented.

4.1 CNC Machining Process Chain

The following CNC process chain was used to show the abilities of its resource efficiency by manufacturing an intelligent medical implant in both single and batch sizes of eight productions. The process chain consists of two solid titanium billets that are manufactured in in two parts, a left and right hand side part. Starting with the solid billets, the CNC machining removes most of the material in order to create the outer profile of the implant. Once the outer profile of the implant is developed, a smaller cutting tool is used in order to machine into the implants the delivery channels required. Following the completion of both the right and left hand sides, a press fit is used in order to combine the two sides through holes on the left hand side implant and 'knobs' on the right hand side. (See Appendix A for visual illustration of the designed part). An illustration of the process used can be seen in the figure 28 below.

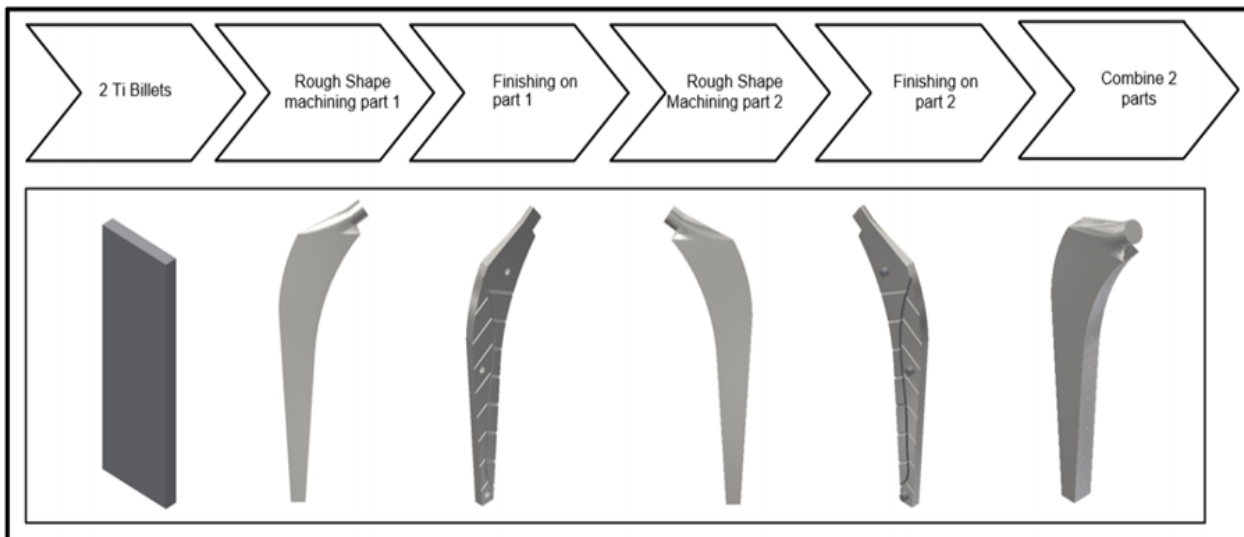


Figure 28: CNC Process Chain for Manufacture of Intelligent Implant



With regards to the resource efficiency, a quantitative study was performed on the time, cost and material, due to the fact that robustness and energy consumption will simply be evaluated as high/low or good/bad respectively.

The following two tables show calculations of the material waste using CNC machining for both single production of the intelligent implant together with the material waste for a production of 8 implants.

Table 6: Table showing the material waste of production of one part (MB – Mass of Billet)

MB1 (Vol = 152mm x 50mm x 8mm)	Mass after Total Left Side Machining	MB2 (Vol = 152mm x 50mm x 5mm)	Mass after Total Right Side Machining	Material Waste
0.274kg	0.063kg	0.1714kg	0.062kg	0.3204kg

Table 7: Table showing the material waste of batch production (mass of Billet)

MB1 (Vol = 240mm x 240mm x 8mm)	Mass after Total Left Side Machining	MB2 (Vol = 240mm x 240mm x 5mm)	Mass after Total Right Side Machining	Material Waste
2.078kg	0.504kg	1.299kg	0.496kg	2.377kg

As seen from Table 6 and Table 7, two different billet sizes were introduced with regards to the single and batch production of the part. For the batch production, the implants were machined from a large biller of titanium hence the reason for increased material waste. This is deceiving however, as through calculations it is seen that 71.9% of material is wasted in the single part production whereas 69.2% has gone to waste through batch production, with specific reference to the starting weight of the billets understandably.

The next key factor effecting resource efficiency with reference to the conceptual framework was time. As seen from the following Table 8, production took roughly 3.5 hours in order to develop a single intelligent. To produce 8 implants it took roughly 15 hours, thus production per unit dropping from 3.5 hours to 1.88 hours. The machining and finishing times of the batch production increase exponentially which is understandable. Machining referring to the production of the outer profile and finishing referring to the machining of the delivery channels and press fit of the right and left hand components.

Incurred costs of the production of the single and batch can be seen in Table below. Prices were taking from quotes received in July 2015.

**Table 8: Table showing the times taking for single and batch production of intelligent implants**

Operation	Single Part Production Time (hours)	Batch Production (hours)
Programming	1	1
Pre-Process Planning (Setup)	1	3
Machining	0.5	4
Finishing	1	8
Total Time	3.5	15

Table 9: Table showing costs of CNC process

Cost Effecting Factors	Price (Rand/kg) (Rand/tool)- α (Rand/hr)- β	Amount Needed for 1 Implant (kg)	Production costs of 1 Implant (Rand)	Production Costs of 8 Implants (Rand)
Titanium Billets	900	0.4554	400.86	3039.50
Aluminium Jig	75	0.5	37.50	37.50
Machining Tool Cost	2500- α	0.1	250	2000
Finishing Tool Cost	2000- α	1	2000	16000
Quote: CNC hourly rate cost	1000- β	3	3000	24000
Cost of Programming	500- β	1	500	500
Total Cost			6188.36	45576.80

Following the quantitative assessment on the identified key factors affecting resource efficiency, a qualitative angle was used to evaluate the robustness and energy consumption of the process. With regards to energy



consumption of the CNC process chain, a medium amount would be used when referring to the tooling specialist, with robustness being good due to the fact CNC machining is utilised in South Africa.

4.2 SLM Machine (Selective Laser Melting) Process Chain

The second evaluation utilises the SLM Machine in order to manufacture a hip implant. A simplified process chain of the manufacturing of the implant is shown in figure below. As mentioned in the literature study in Chapter 2, the SLM process uses Titanium powder in order to develop the part in a layer-by-layer process. DFM and DFA is crucial for this instance as the orientation of the build needs to be perfect in order to reduce the time of the build. Manual finishing operations are also demanded as the material needs to be removed from the base and the support structures. Removal from the base and support structures can either be done through wire cutting or manually.

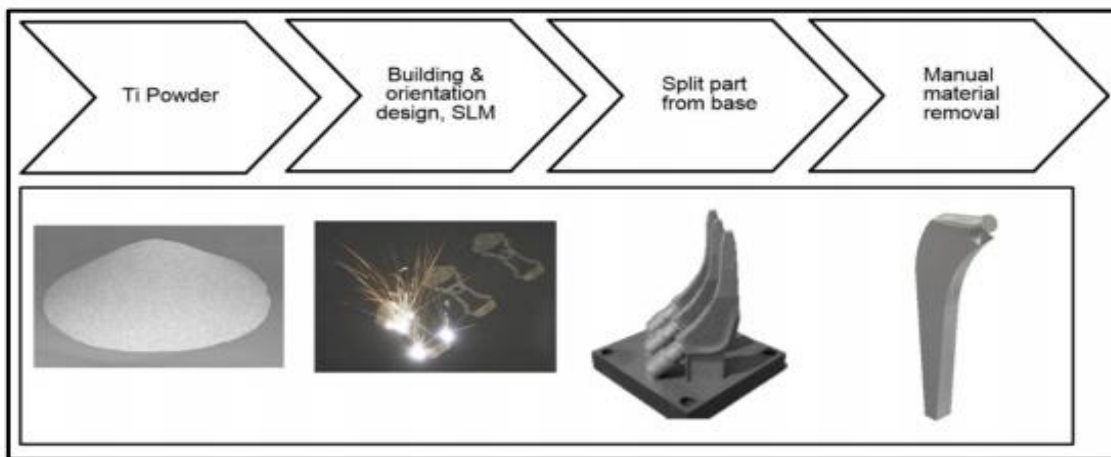


Figure 29: SLM Process Chain for Manufacturing Hip Implant

As with the previous evaluation, both single and batch production of the SLM processes are compared. Specialists currently estimate that 5% of the Titanium powder used in the build will go to waste. Other material waste includes the support structures of the build which come to roughly 10% in weight of the final part.

The Table 10 below shows the material waste associated using SLM as a process chain to manufacture a hip implant for both single and batch production.

**Table 10: Table showing material waste for SLM process**

Production Size	Powder Mass (kg)	Final Mass (kg)	Material Waste (kg)
Single	0.1426	0.124	0.0186
Batch	1.141	0.992	0.149

Referring to the framework, the next factor evaluated was the time of the manufacturing process. The building time for single production using the SLM process was a quarter of the time when compared to the batch production. This is due to the fact of the different orientations used when developing the two different production volumes. When batch manufacturing using the SLM process, the DFM and DFA requires that 8 implants be developed on the base plate, thus requiring a different orientation. Following this, the increase in build time has a direct influence on the cost of the process. Due to the hourly rate tariff, cost and time are dependently linked to one another. The tables showing the data of the times and cost of the SLM process can be seen on the following page.

Regarding the quality and energy consumption of the SLM process, a medium amount of energy was used according to the tooling specialists and when compared to similar size build for both the batch and single production. With regards to the quality control aspect of the framework, the components were measured out and designed well within the medical requirements through CAD.

Table 11: Table showing SLM Processing Times

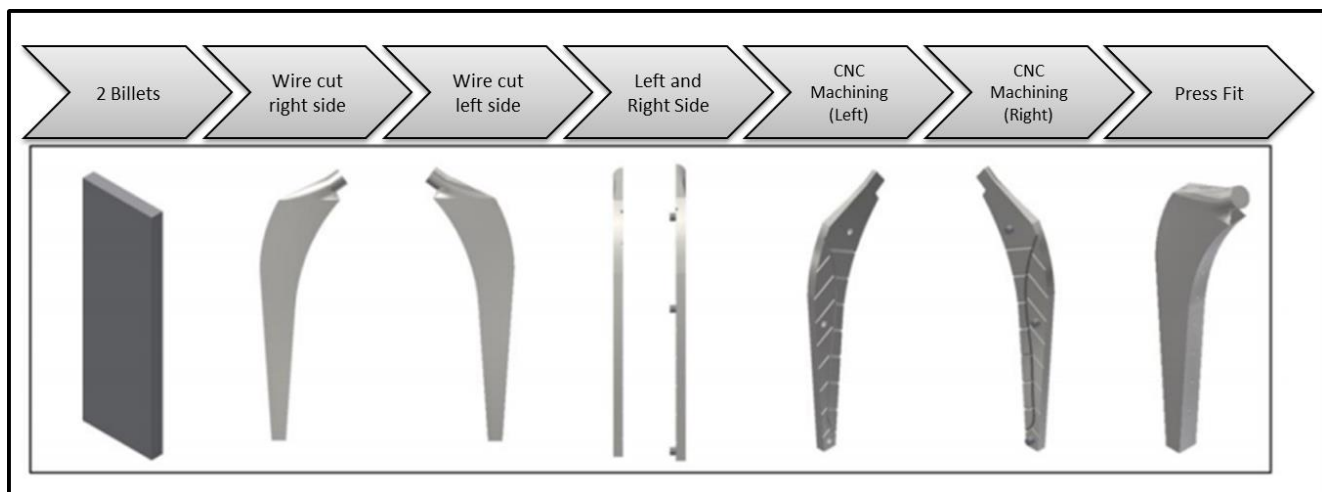
Operation	Single Part Production Time (hours)	Batch Production (hours)
Programming	1	1
Pre-Process Planning (Setup)	2	2
Build Time	4	40
Finishing	2	16
Total Time	8	59

**Table 12: Table showing costs of SLM process**

Cost Effecting Factors	Price (Rand/kg) (Rand/hr)- β	Amount Needed for 1 Implant (kg)- α (hr)- β	Production costs of 1 Implant (Rand)	Production Costs of 8 Implants (Rand)
Titanium Powder	900	0.1426- α	1069.50	8557.50
Hourly Rate for SLM Process	2500- β	4- β	4800	48000
Finishing Operations	2000- β	2- β	700	5600
Cost of Programming	500- β	1- β	500	500
Total Cost			7069.50	62657.50

4.3 Wire Cutting and CNC Machining (Hybrid Process) Process Chain

The final manufacturing technique for investigation of resource efficiency uses a combination of two different manufacturing technologies, namely wire cutting and CNC machining, forming a hybrid process. Similarly to the process chain involving only the CNC Machining in Chapter 4.1, two billets are used and shaped into the outer profile of the implant using the wire cutting technology. From here the finer machining of the delivery channels of the implant are performed using CNC machining. The part will then be joined using a press fit. The process chain of the manufacturing of the implant is illustrated in the figure below.

**Figure 30: Process Chain of Hybrid Process, Wire Cutting and CNC Machining**



Traditionally, wire cutting is not a manufacturing technology that is used for batch production, unless highly complex build orientations and clamping strategies are used. Thus for this process chain case, only single part production is evaluated.

Due to the fact that the same billet sizes as previously used are utilised for this process chain, material waste for the entire process chain of wire cutting and CNC machining was identical to that of the pure CNC machining process chain, as shown in the table below.

Table 13: Table showing material waste of the Hybrid Process (MB – Mass of Billet)

MB1 (Vol = 152mm x 50mm x 8mm)	MB2 (Vol = 152mm x 50mm x 5mm)	Mass after Wire Cut and CNC Machine (Left)	Mass after Wire Cut and CNC Machine (Right)	Material Waste
0.274kg	0.1714	0.063	0.062	0.3204kg

With regards to the material waste of the wire cutting process, the Titanium being removed from the billets are not chips and thus can be used again for odd solicitations requiring material of that specific removal size.

In order to produce the part through the wire cutting and CNC process chain, a total time of 4.2 hours will be needed with a cost of R4688.36 per implant produced. A summary of the cost and time associated with the wire cutting and CNC machining strategies shown on Table 14 and 15 below.

Table 14: Table showing the manufacturing time for the Hybrid Process

Operation	Part Production Time (hours)
Programming	1
Pre-Process Planning (Setup)	0.2
Wire Cutting Outer Profile	2
Finishing using CNC Machining	1
Total Time	4.2

With regards to robustness and the energy consumption, the tool specialist identified this technique as medium in terms of the energy consumption when related to projects of similar size. This process chain can also be seen as



robust due to the fact that both techniques are currently well recognized in the manufacturing industry of South Africa. The only limitation on this process would be the size of the billets used in the production of the component. This is due to the fact, if parts are needed to be produced at a commercial level, skilled professionals will be required at all times to set up the orientations of the billets and have to essentially man the entire production process, hence the reason batch production was not considered in this evaluation.

Table 15: Total costs associated with Hybrid Manufacturing process chain

Cost Effecting Factors	Price (Rand/kg) (Rand/hr)- β (Rand/tool)- α	Amount Needed for 1 Implant (kg)- α (hr)- β	Production costs of 1 Implant (Rand)
Titanium Billets	900	0.4454- α	400.86
Aluminium Jig	75	0.5- α	37.50
Hourly Rates (Wire Cutting)	375- β	2- β	750
Machining Tool Cost for Finishing	2000- α	1	2000
Hourly Rate (CNC Machining)	1000- β	1- β	1000
Programming Costs	500- β	1- β	500
Total Cost			4688.36

4.4 Framework Validation

As seen from the quantitative analyses above, the framework is able to be used in order to investigate the resource efficiency different Titanium manufacturing process chain. The framework was able to identify some of the key factors affecting the resource efficiency of the different process chains and thus can be used to evaluate and compare different manufacturing process chains in order to determine the most resource efficient chain. Regarding the above process chains, through the framework it was identified that the most resource efficient for single production of the intelligent implant would be the hybrid process of the wire cutting and CNC machining, due to the results achieved from this process. For batch production respectively, the CNC machining would be the most resource efficient chain to use. Even though there is more waste for the CNC process chain, the time comparison between CNC machining and SLM varies extremely, therefore meaning costs and energy consumption are affected negatively as well. DFM and DFA for the SLM strategy will also have to be



thoroughly worked through as support structures will need to be developed and the build orientation of the will have to be thoroughly revised in order to reduce build time while maintaining high quality of the component. In order to evaluate the framework, an overall qualitative assessment of the framework was performed on the three process chains evaluated as illustrated in the figure below and summarised in Table 16. The factors in the framework were given score ratings by the manufacturing specialists in accordance to the process used and how he felt the process fared.

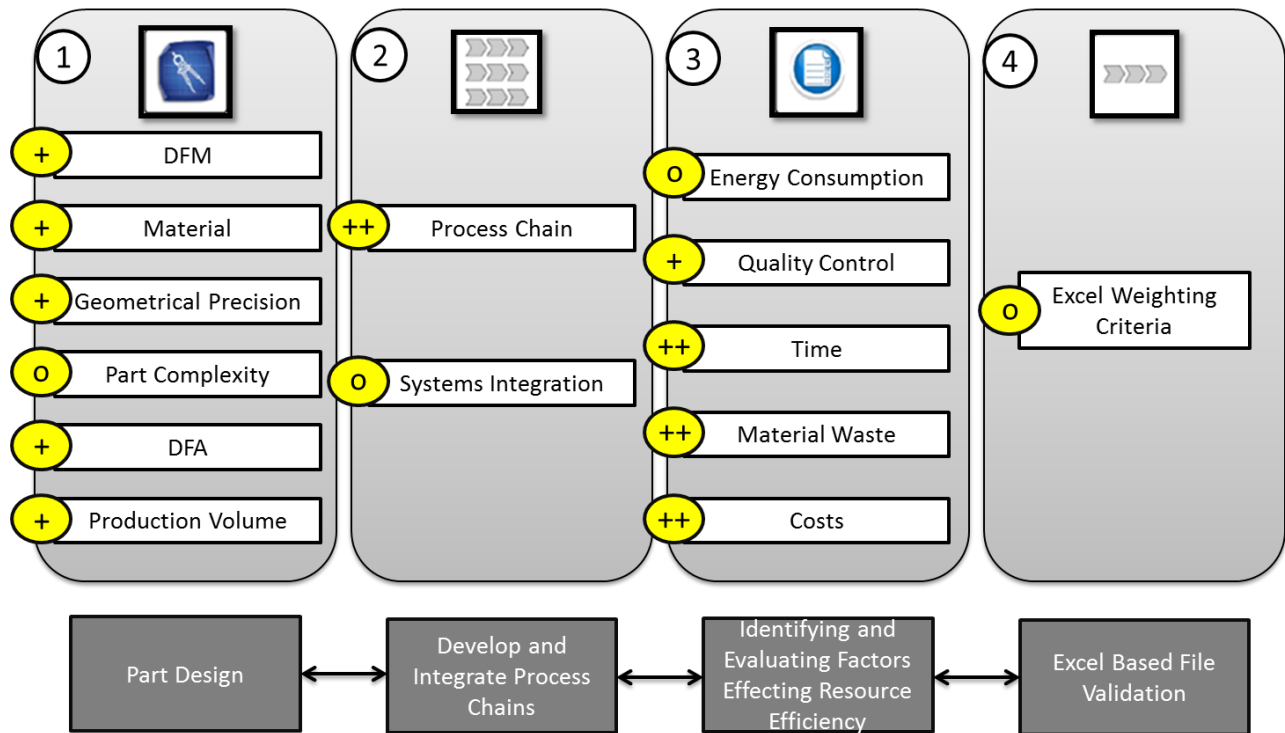


Figure 31: Qualitative Assessment of Conceptual Framework (++...very good, +... good, o...neutral, - ...poor, - -...very poor)

4.4.1 Part Design Validation

In terms of the factors effecting the DFM of the process, the material selection was good due to the fact that Titanium and aluminium jig were required for the implants. The geometrical precision was well with reference to the CAD drawings in the Appendices. The part complexity was shown a neutral due to the fact that, even though it was a freeform object and acute delivery channels were designed, the actual complexity of the implant was standard when compared with other Titanium freeform productions. As previously mentioned, production volume, DFM and DFA were all well organised in terms of the single and batch production respectively and in terms of the different ways the implants could be manufactured in order to optimise orientation and resource efficiency.

**Table 16: Summary of Qualitative assessment of the process chains using the conceptual framework**

1. Part Design		2. Develop & Integrate Process Chains		3. Identifying & Evaluating Factors effecting Resource Efficiency		4. Excel Based File Validation	
DFM	+	Process Chains	++	Energy Consumption	o	Excel Weighting Criteria	o
Material	+	Systems Integration	+	Quality Control	+		
Geometrical Precision	+			Time	++		
Part Complexity	o			Material Waste	++		
DFA	+			Costs	++		
Production Volume	+						

4.4.2 Develop and Integrate Process Chain Validation

The process chains were thoroughly developed in accordance to test and evaluate the resource efficiency of each. There was however only one hybrid process assessed meaning the integration of the different systems was neutral when referencing the framework.

4.4.3 Identifying and Evaluating Factors Effecting Resource Efficiency Validation

The key factors of the process chain were correctly identified in the framework with each process having a large impact on the resource efficiency of the different process chains. Time, Cost and Material waste were taken into detailed consideration with a quantitative analysis on each hence the reason their ‘very good’ validation rating. A neutral score was given to the energy consumption as energy optimisation techniques were not considered.

4.4.4 Excel Based File Validation

Due to the fact that the excel based model will be based on the final framework after the iteration refinements, the file was still in the development stages.



4.5 Shortcomings and Possible Changes to the Conceptual Framework

Through the first iteration and validation of the conceptual framework a number of shortcomings were realised with specific reference to the development of a resource efficient process chains. Through the hip implant process chains, it was realised that the framework essentially focuses on the basic aspects of designing a resource efficient process chain. The framework lacked the ability to show users the aspects such as design for additive manufacturing and design for subtractive manufacturing in the '*Part and Process*' design phase. This is due to the fact that the build designs for the SLM machine needed to be specifically oriented with support structures in place, which impacts process chain resource efficiency.

Another aspect to be considered is the process chain developed in order to make a resource efficient component essentially. Different manufacturing technologies have different inputs and outputs as seen from the case studies above, thus considerations of what strategy to go about is required.

Following this, a floor that was realised was also the machine capability profile. With reference to the wire cutting and CNC machining process, the hybrid process was deemed as infeasible to produce components in batch due to the fact that the hybrid process simply did not have the capability of producing components simultaneously.

Influences on manning of the machines was also not taken into consideration in the conceptual framework which does clearly have an impact on the resource efficiency of the any manufacturing process chain. The human factor plays a significant role in producing a quality part and therefore the knowledge and experience of the operator is important. Inadequate knowledge and experience can inevitably lead to parts that are insufficient for application, and thereby add to process waste. In addition to this, an appropriate environment for AM and SM machines must be maintained. Together these practices can reduce the impact of human error or negligence.

With regards to the surveys conducted (refer to Appendix F), various responses were evaluated and considered for the next framework.

A list of the shortcomings that need to be considered for refinement of the framework model are namely:

- There is currently no design for AM or design for SM within the framework for user consideration
- With regards to the AM outlook, there are different ways in which the manufacturing technologies are able to enhance product performance
- Another aspect that needs to be initially considered is that of, when planning the process, what can be implemented for material waste reduction



- Support Structures with regards to the AM technology will also have a substantial impact on the resource efficiency
- Human Factors will also play a role in the efficiency of the process
- Capability of the machines manufacturing the product will have to be factored as well in order for manufacturers to decide the best possible way to develop the product.
- Understanding of Framework on first glance
- Topic of the framework (Heading)
- Templates for the framework and design experiments
- 6R's of manufacturing incorporation
- Processing Parameters of manufacturing
- Post-processing procedures
- The flow of the framework to make it user-friendly



5. Development and Validation of Framework V_1 : Iteration 2

The following chapter presents the validation of the refinement of the conceptual framework into a new developed V_1 framework. The new framework will be used to serve the same function as the conceptual framework, investigating the resource efficiency of different process chains. The new framework will be used to evaluate the resource efficiency of the production of an aerospace component known as the ‘knuckleduster’.

5.1 Development of Framework V_1

The shortcomings of the conceptual framework were taken into consideration in order to update and develop the framework illustrated in Figure 32. As seen in the new Framework V_1 , the theme of the framework has now been given. The excel weighting in the last phase of the conceptual framework has also been removed as currently it won’t be used to evaluate the resource efficiency until the final framework is developed and implemented. The theme of the second phase in the conceptual framework has now been combine into a singular category, ‘*Part and Process Design*’, therefore leaving a ‘*Process Planning*’ and ‘*Process Qualification*’ category open for phases two and three respectively. These categories were too chosen by analysing a typical manufacturing process chain and breaking the process chain down into sub-categories as shown previously in the conceptual framework development. Again these phases were developed with specific consideration towards titanium manufacturing process chains. With the new naming of the categories, it should allow for easier understanding of each phase to produce and evaluate resource efficient components.

5.2 Framework Overview

The framework essentially explains the product through consideration of various process factors to produce the most resource efficient product. Resource conscious production is at the core of the framework and potential AM and SM technologies should focus on process chains that are suitable to produce high quality parts using as few resources possible. For continuous reduction of resource utilisation in both AM and SM based process chains, evaluations of all processes within the chain are required. When evaluating the respective processes, quality control (geometrical precision, surface finish, etc.), energy consumption, manufacturing time (setup-, waiting- and programming times), material wastage and costs are key considerations of qualifying the process as resource efficient.

The factors included in the different categories of the framework are discussed in the chapters that follow.



5.2.1 Part and Process Design

Part and Process design is the new first phase for the framework. Much like before, the process chain rationale refers to the development of different process chains in order to manufacture a titanium component. The thought behind the inclusion of the rationale is in order for the user, when looking at the framework, to justify the reason as to why they are using the specific process chain for the manufacture and the, advancedly speaking, resource efficient advantages of such a designed process chain.

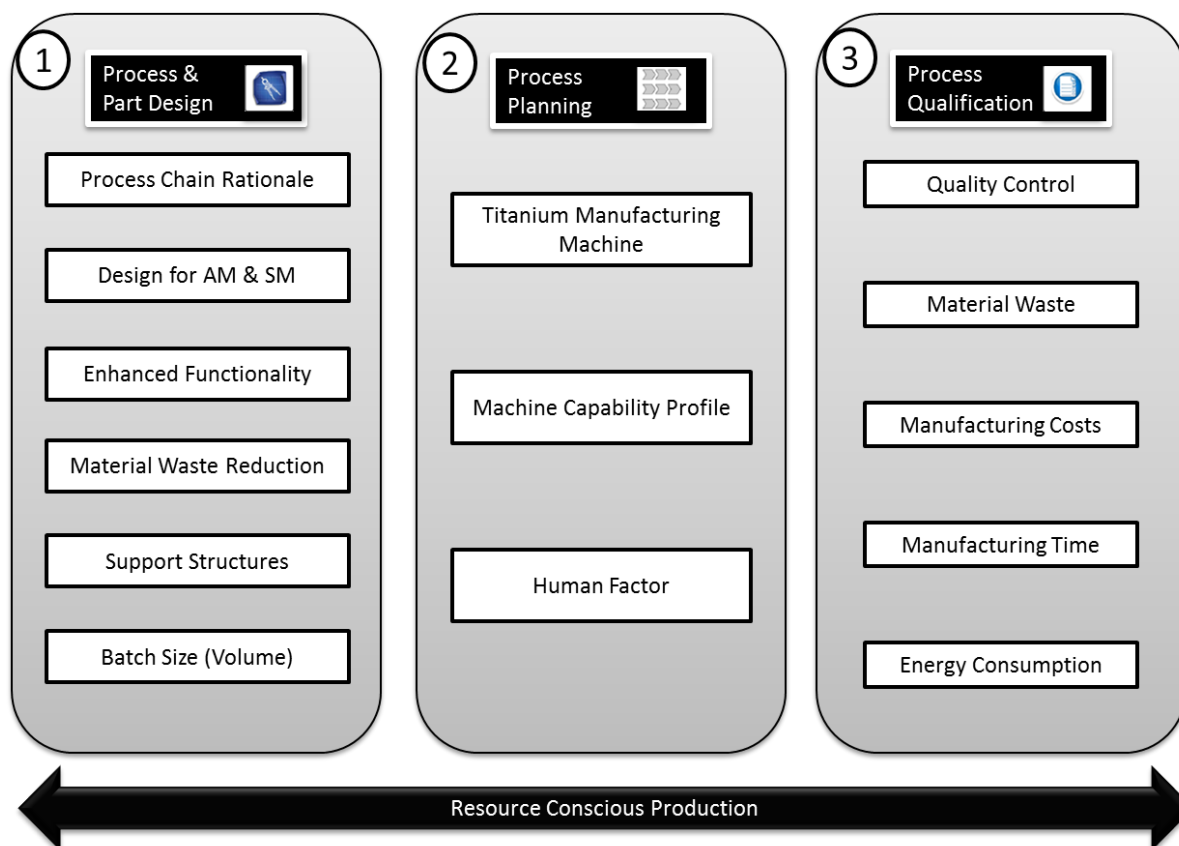


Figure 32: Refined and Developed V_1 Framework

The next addition to the framework is designing for additive- and subtractive manufacturing. Certain factors require careful consideration when designing for AM and SM. Dimensional and statistical accuracy of the machine should be established prior to part design. It has been found that differences in machine capabilities challenges in standardising. An example of this includes machine specifications (envelope size, geometrical capabilities energy source diameter, scanning speed, scanning strategies and preheating) which are specific to the type of design and manufacturer. Nevertheless, a number of focus areas generally apply to most powder bed fusion processes. These emphasise optimising surface topology and material usage with respect to part features



such as thin walls, holes, overhangs, radii, and the building orientation [126] [127]. Furthermore, the need for highly customised parts, specific to potentially unique applications, has led to collaborative design platforms, especially for medical implants, allowing efficient design iterations with surgeons actively involved in the design and evaluation processes [128].

Enhanced functionality specifically refers to the AM process chains respectively. This is due to the fact that the design freedom of AM allows for the inclusion of complex conformal cooling channels in moulds that is not possible by conventional means. Tools with conformal cooling have proven to provide significant advantages in the control of tool temperatures, moulded part dimensions, and cycle time reduction [129] [130]. The initial cost of producing a mould with conformal cooling might be higher, but the savings in cycle time and improved quality for each part thereafter leads to savings that exceeds the initial extra cost. Medical implants is another area where AM have potential to enhance functionality.

Material waste reduction for this phase is not seen as evaluating factor such as in phase 3 of the framework. The incorporation of Titanium AM and SM into the process chain can be specifically advantageous for parts with high buy-to-fly ratios, which is characteristic of aerospace components. Production of such parts is usually performed by machining processes and up to 95% of material can end up as waste [131]. It has been reported that a ratio of 12:1 and higher could be produced more economically by AM. This is therefore also one of the key areas where SM and especially AM can add value to products [132].

An important consideration in preparing the build is the efficient incorporation of support structures. They are additional structures that support certain features of the part (for example overhangs) by fixing them to the base. They also allow for heat dissipation. It is non-value adding, and resources used for support generation should be minimised as they often end up as waste. The resource usage includes material, energy, and time during building as well as removal processes thereafter. When optimised, support material waste can be reduced up to 45%, hence the reason for the inclusion [133].

With regards to the conceptual framework, batch size was an important characteristic when evaluating the resource efficiency of the implant and thus needs to be taken into real consideration in the process planning phase of the framework as this in turn will have a major impact on the final resource efficiency of the product.

5.2.2 Process Planning

The actual machine to be used for any AM or SM process must be carefully evaluated. Different machines have different resource inputs, outputs and wastages. Machine acquisition cost is one of the most significant costs involved in both AM and SM. In 2011 the average price of an industrial AM system was \$73,220 [134]. Titanium AM and SM machines require additional equipment such as nitrogen generators, special vacuum



cleaners and, sieving stations, adding substantial extra costs. Material, consumables and service technicians are limited or non-existent in certain countries and have to be sourced from supplying countries, resulting in further additional costs and potential time delays. Thus therefore, all accumulating to into the consideration of resource efficient production.

A capability profile involves a comprehensive study of the machine's processing capabilities with respect to technological, mechanical, and metallurgical properties. Mechanical properties such as strength, density, hardness, fatigue, residual stress, ductility, elongation, and fracture toughness are all part of a proper capability profile. These properties can be altered by different processing parameters, and should therefore be optimized for a specific material. The microstructure of AM parts can be altered with various post-processing heat treatments [100] [135]. Laser melting of metal powder induces residual thermal stresses into the parts. Osakada & Shiomi showed that high tensile stresses occurs on top surfaces (furthest from the building plate) and on bottom surfaces (closest to the building plate) while compressive stresses exist in the middle region of the part [136]. Residual stress can include fractures and/or lead to deformation of parts. Preventative measures include heat treatment of parts, re-melt strategies, and preheating of the build plate.

With regards to the human factor aspect of process planning, training alone for operating an AM and SM machines is often not sufficient. The human factor plays a significant role in producing a quality part and therefore the knowledge and experience of the operator is important. Inadequate knowledge and experience can inevitably lead to parts that are insufficient for application, and thereby add to process waste. In addition to this, an appropriate environment for AM machines must be maintained. Proper ventilation with constant room temperature and minimal dust are required. Experience has shown that AM machines should not be switched off for extended periods, since this can cause machines to have errors during start-up. Large UPS systems are expensive, but essential to avoid potential electronic failures on machines. Together these practices can reduce the impact of human error or negligence while simultaneously allowing for a more resource efficient manufacturing process.

5.2.3 Process Qualification

When building functional parts with AM and SM in either batch or single sizes, it is important to perform a detailed non-destructive inspection, as defects might still be present. As mentioned in the literature, defects and rejects of manufacturing builds highly affect the value stream of the process chain and thus highly impact the efficiency of the build and future builds if not corrected. Most notably these include; residual porosity, internal cracks or insufficient fusion of layers, surface cracks or inadequate roughness, geometrical distortion due to inadequate support structures, and geometrical deviation and delamination due to residual stresses. Internal



inspection can be performed by computed tomography and geometrical inspection by tactile processes such as co-ordinate measuring or optical scanners. This is a challenging factor for reducing resource usage when producing single parts, for batch production, however, a statistical sampling strategy could reduce time and cost for inspection.

As researched, material waste has a large impact on the resource efficiency of a manufacturing process and thus throughout production, waste needs to be measured in order to evaluate where the process can be optimised. Regarding the AM process, material waste can essentially be reduced by optimising build supports, or in areas involving the design and build orientation. Contamination of the produced parts also has an influence on wastage, as dust or debris could pollute the part being manufactured. Material waste in context of the application in Chapter 2 is defined as the difference in the volumes of the part produced from powder compared to a subtractive process from a solid billet, and further evaluated accordingly.

With regards to the manufacturing time, manufacturing cost and energy consumption, refer to the literature presented in Chapter 2. In summary, these factors have many branches which affect the resource efficiency of a production process and thus must be highly considered and completely evaluated for any manufacturing process. When recording costs, branches such as the material, component labour and machine costs must all be taken into account in order to complete a true cost modelling analysis of the process chain. When performing the time analysis, different areas affecting the process chain such as cycle time and downtime must all be taking into account as these, as previously mentioned, are contributors of the resource efficiency of the process chain.

AM processes such as SLM and SLS consist of technologies where energy consumption is not necessarily optimised. In order to compare the energy of the various AM strategies, an efficiency factor of the laser process exists, which shows its ability to convert powder from the grid into heat for melting. Power consumption of specific AM machines should be evaluated and compared to that of machines otherwise used for conventional processing. An important trade-off is energy consumption versus processing time. An example includes total energy requirement that differ according to geometry, support structures, build orientation, and process parameters, which ultimately influences the building time [137].

5.3 Component Build and Results

The component selected for the second iteration of the framework was that of an aerospace component called the ‘Knuckleduster’. Based on a purely machining point of view, in order to produce this part about 90% of the titanium material is removed from the solid billet. The given high percentage showed that there was a high potential for possible resource saving in the forms of material, cost and manufacturing time. In order to prove the above statement, CAM simulations were run. The CAM software showed that by combining both the additive



and subtractive manufacturing process, possible savings of material were as high as 80 – 90% and a machining time saving of 15-25%.

Due to the fact that this titanium component was previously built, the machining and cutting strategies were optimized using the CAM software. From this optimisation the billet was then CNC machined. The cutting parameters and machine tool path can be found in the appendices. The tool wear was also evaluated during the cutting operations using the Olympus GX51 optical microscope.

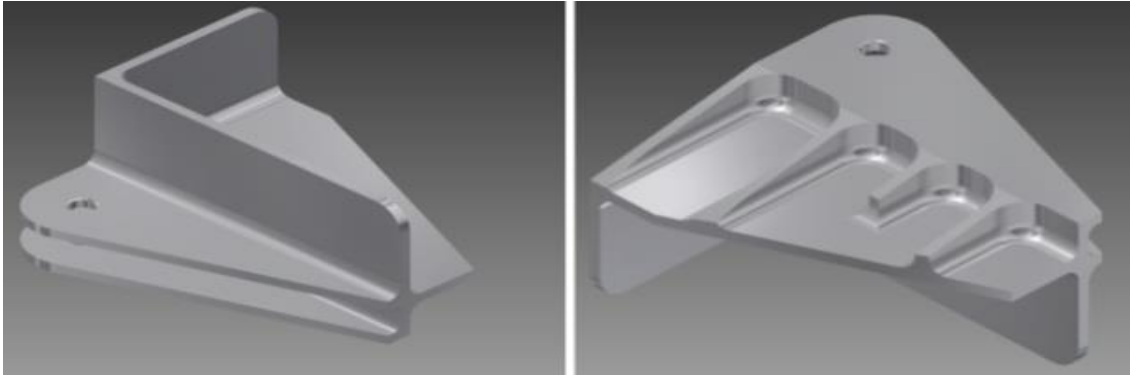


Figure 33: Aerospace Component Knuckleduster - Top and Bottom view

For the hybrid process of both additive and subtractive manufacturing, the first manufacturing process used was the SLM process in order to produce a near-net shaped part. For this build, support features were utilised in the areas of the knuckleduster that had undercut angles of above 45 degrees. In order to compensate for the machining process after, a 1mm layer was set on the near-net shaped for allowance. Using the Titanium Ti-6Al-4V powder, the component was developed by the SLM process through by selective melting, scanning and fusing the powder in a layer by layer process as mentioned in Chapter 2, in order to produce the near-net shaped part. From here, the near-net shaped part was then measured using the GOM system to make sure the tolerances of the part were within the used tolerances. Following the measurements, the near-net shaped part was placed in the CNC machine for the semi-finishing and finishing operations. As previously mentioned, the parameters and setups for both the CNC machining and the SLM process can be seen in the Appendix B. The two different process chains for the manufacturing of the part are shown in Figure 34 and Figure 35.

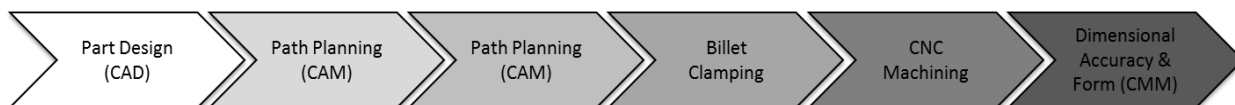


Figure 34: Purely conventional CNC process chain one for the manufacture of the Aerospace component



Figure 35: Hybrid Process Chain two, combining the SLM and CNC machining for the manufacture of the aerospace component

Once the part finished component had been manufactured using the two different process chains, the following results were documented and evaluated. The manufacturing time and material removed results for the two different setups are summarised in Table 17. For both the setups, the majority of the material was removed through the roughing operations of the part. The finish operations were performed in order to increase the accuracy and the surface finish for improved customer/user satisfaction.

On completion of the SLM process, the accuracy was measured in order to calculate the deviation from the STL file. A maximum deviation was measured to be 0.32mm with the GOM results illustrated in Figure 36. As previously mentioned, only semi-finishing and finishing operations for the first setup of the SLM process due to the material allowance of 1mm given. This was evident with the time saving of 47% and a material saving of 97% when compared to the purely CNC machining process chain. For the second setup, the support structures were removed through roughing operations. Due to this fact, the resource efficiency of the process chain was decreased as the support material went to waste with the time efficiency being decreased as a result of the tool path. When comparing the two processes in terms of material and time, the hybrid combination was more resource efficient.

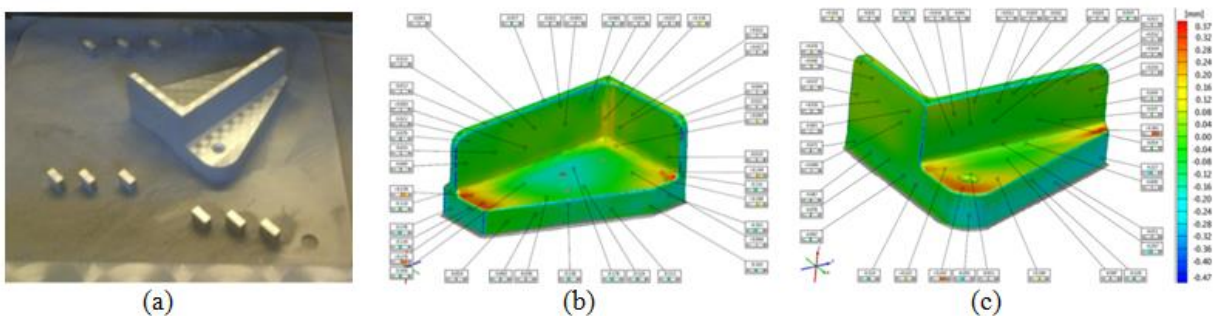


Figure 36: Knuckleduster component for the SLM process chain: (a) finished product; (b) GOM Results- Front View; (c) GOM Results- Rear View

**Table 17: Machining Times and Material removed of the CNC vs Hybrid Process**

Part	Setup 1			Setup 2			Total		
	Material Removed [cm ³]	Time [min]	Cost [Rands]	Material Removed [cm ³]	Time [min]	Cost [Rands]	Material Removed [cm ³]	Time [min]	Cost [Rands]
CNC Machine	394	66	1485	107	99	2227.5	501	165	3712.5
CNC Machine & SLM	11	35	1662.38	53	95	2137.05	64	130	3799.43
Saving	383 (97%)	31 (47%)	-177.38 (0%)	54 (51%)	4 (4%)	91.45 (4%)	437 (87%)	35 (21%)	-86.93 (0%)

Following the framework, quality control of the component was evaluated through part inspection using the CMM machine. Results showed that there was a deviation 178 μ m for the part that was CNC machined and a deviation of 301 μ m for the hybrid processed part. Further inspection showed standard errors of 3 μ m and 4 μ m for the CNC and hybrid process respectively together with means of 11 μ m and 40 μ m respectively. Evaluating these figures it shows that the hybrid process had more extreme lower and upper values for the part inspection, essentially affecting the accuracy of the component. That being said, the accuracy for both parts was in the tolerance range for the required aerospace applications. When comparing the two process chains, the hybrid process shows less accuracy than the pure CNC machining. This could be due to the fact that the hybrid process had a more complex setup when compared to the CNC process. The results for the deviations are illustrated in Figure 37.

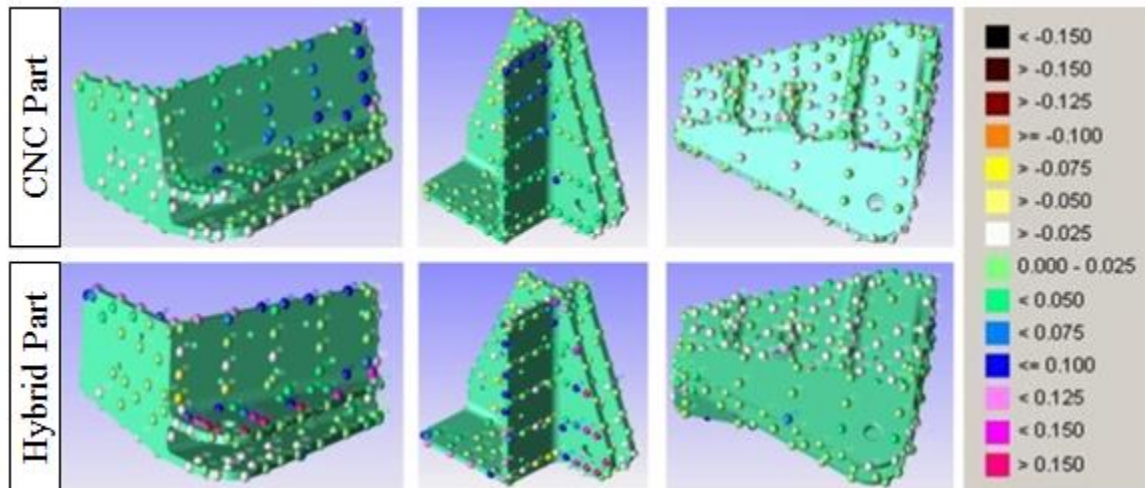


Figure 37: CMM Results of the both the CNC Part and the Hybrid Component

5.4 Framework Validation

As seen from the manufacture and the results documented for the aerospace component, the framework V_1 proved to be a helpful guide into resource efficient production. Through the identified key factors and the various process planning parameters illustrated in the framework, a thorough analysis was able to be performed into a resource efficient production of the knuckleduster component. With specific reference to the framework, it was identified that when comparing the two different processing strategies used to develop the component, the hybrid process of the CNC machining and SLM was the most resource efficient overall. A qualitative assessment of the framework V_1 is illustrated in Figure 38 and Table 18. The figure shows the way qualitative assessment performed with regards to the two process chains followed by a summary of the assessment in tabular form. Again a score rating has been used in order to validate the framework and investigate the process chain. This evaluation was performed by the manufacturing specialist in terms of he saw the various factors affecting the resource efficiency of the process chain faired to the actual manufacturing process.

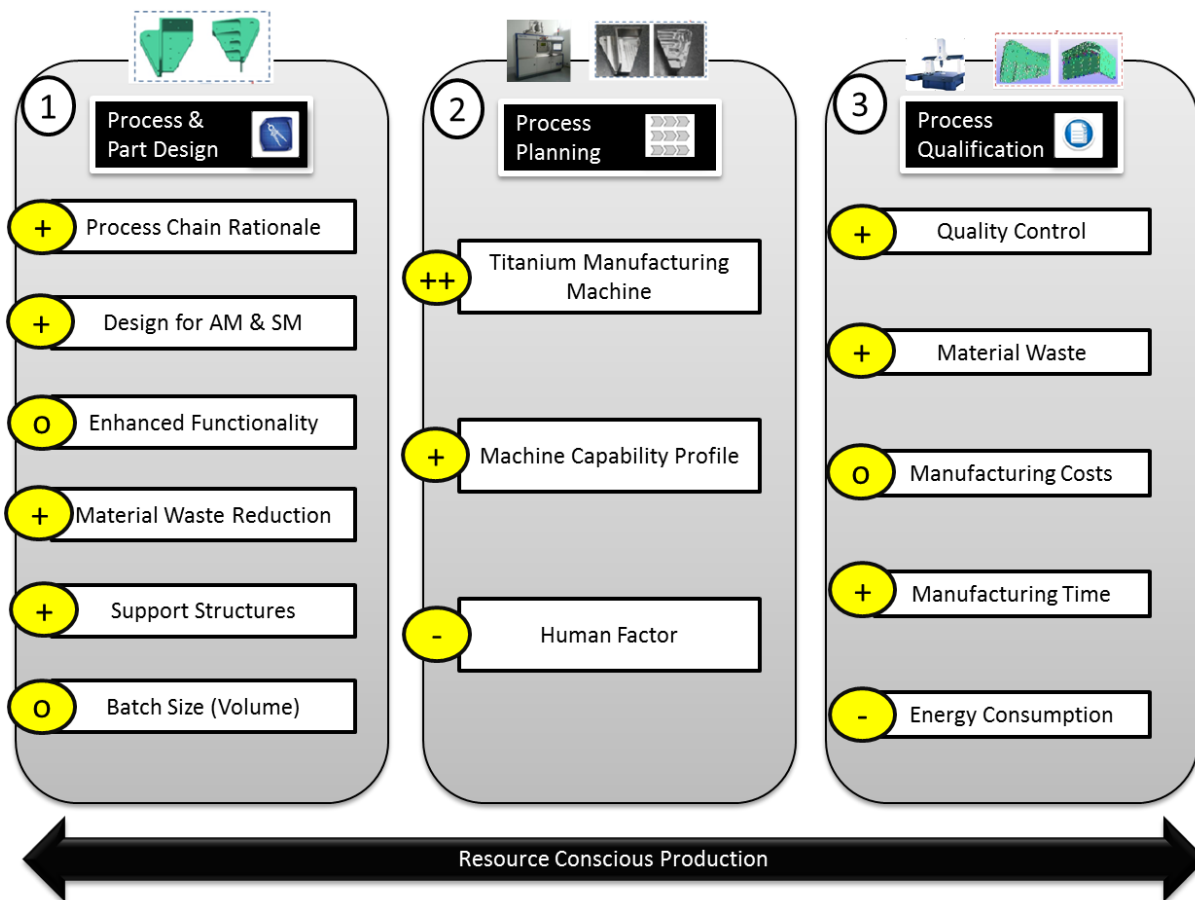


Figure 38: Qualitative assessment of framework V₁ (++)...very good, +... good, o...neutral, -...poor, - -...very poor)

Table 18: Summary of the qualitative assessment of framework V₁

1. Process & Part Design		2. Process Planning		3. Process Qualification	
Design for AM and SM	+	Metal AM Machine	++	Quality Control	+
Enhanced Functionality	o	Machine Capability Profile	+	Material Waste	+
Material Waste Reduction	+	Human Factor	-	Manufacturing Cost	o
Support Structures	+			Manufacturing Time	+
Batch size	o			Energy Consumption	-



5.4.1 Process and Part Design

As previously mentioned, the part is designed to be manufacturing using a subtractive manufacturing process. However, due to previous builds, the design of the process for the manufacture was optimised and enhanced, hence the score ratings for these factors in the framework. Due to the fact that an AM approach was used, it allowed for material saving as the processes were optimised and that, when compared to manufacturing using traditional cuboidal billets, the layer-by-layer SLM process produces much less waste. That being said however, the support structures needed for the SLM process did provide excess waste and hindered the manufacturing time as roughing operations were needed for them. With regards to the batch size, a neutral score was given as the component manufacturers knew two different process chains were being compared and thus produced one component for each process respectively.

5.4.2 Process Planning

Forming part of process planning, assessment of the machine and its capability profile revealed that it was more than sufficient for the intended manufacturing process and purposes, yielding positive scores. Limited knowledge on the process parameters and efficient utilization of the machine capability at the time of manufacture, however, limited the full potential attainable with the specific process chain and therefore resulted in a poorer rating.

5.4.3 Process Qualification

Process qualification involved the evaluation of key indicators coupled to the process chain outcome. The quality was evaluated using geometrical precision analysis and surface finish measurements. The tolerances of the demonstrator component were within the specified values giving a positive score. Compared to a purely subtractive process, the AM build time associated with this component was significantly longer than and therefore incurred much higher manufacturing costs and times, resulting in very poor ratings. In addition, the long build time increased energy consumption, which also contributed to a poor rating for the process. That being said, the correct value of the consumption was not calculated as it was not in the scope of the experiment. Validation of the framework therefore illustrates how the resource efficiency can be evaluated qualitatively to assist process planners with decisions regarding implementation of certain process chains.

5.5 Shortcomings and possible changes to Framework V₁

Through the second iteration of the framework, it was proven that the framework provided the user with the aspects affecting resource efficiency and for the reason that there were a number of changes to the conceptual framework, a limited amount of changes and shortcomings to the key factors of resource efficiency were found in framework V₁. Thus by referring to it, one can utilize ‘resource conscious production’. That being said



however, it was noticed that the framework lacked other manufacturing processes that are capable of being used in Titanium manufacturing. In the current framework V₁, the initial ‘*Process and Part Design*’ section includes a factor: Design for AM and SM. When referring to Titanium manufacturing, there are a number of other manufacturing options and processes that can be accounted for. These manufacturing technologies include dividing, forming and joining, all of which can be used in combination and hybrid processes together with AM and SM. There are currently seven main process combinations that need to be accounted for in the framework and they are namely forming, additive, subtractive, joining and subtractive, additive and subtractive, forming and subtractive and forming and additive [138]. Therefore thus, instead of designing only for AM and SM, combination processes will be included in the ‘*Part and Process Design*’ step.

Following this, another aspect that needed to be changed was the understandability or user friendliness of the framework. Currently looking at framework V₁, it is simply lists/columns of factors effecting resource efficiency. In order for a framework to investigate the resource efficiency of a process chain fully, different steps should be followed accordingly, allowing for users to thoroughly consider the reason for manufacture together with the many parameters they are able to change in order for there to be a fully value adding process chain with minimal waste.

With regards to the surveys conducted (Appendix F) for the second framework, various inputs were considered for the framework V₂. These considerations are as follows

- Design of Process Combinations with regards to all the Titanium manufacturing processes
- Developing a more understandable framework by providing logical steps to follow and essentially a ‘process chain’ for the user/manufacturer
- Machines only for titanium do not exist and thus this factor should be changed
- Limit on the system and the framework (technology level, process level)
- The limits for resource efficiency are not present
- Template should be used in order for the understanding of the framework and for the user to use whilst running through the framework (this will be presented in accordance to the V_{Final} framework and will be illustrated in Appendix F)
- Framework does not flow/not user-friendly
- 6R’s still not present
- Process and Part Design is only focused on AM



6. Development and Validation of Framework V₂: Iteration 2

The following chapter presents the validation of the refined V₁ framework. The new framework (V₂) will be used to serve the function of investigating resource efficient production. The framework will be used to investigate and evaluate the second production of an aerospace component known as the ‘banana brace’.

6.1 Development of Framework V₂

As mention in Chapter 5, the shortcomings identified for the framework were taken into account and changed for the new framework. Like Framework V₁, the theme of resource conscious production has remained together with the three main identified sections to utilize for resource efficient production: *Part and Process Design*, *Process Planning*, and *Process Qualification*. The framework has however now incorporated these three sections into three different categories namely, Resource Conscious Production, Efficiency Evaluation and then Resource Efficient Process Chains. This allows for users to essentially follow the steps to incorporate resource efficiency into their production.

6.2 Framework Overview

Much like framework V₁, framework V₂ essentially explains the product through consideration of various process factors to produce the most resource efficient product. As seen in Figure 39, Resource Conscious Production of Titanium components is at the core of the framework. The framework now however is divided into 3 categories, A, B and C which each follow a different theme:

- A - Resource Conscious Production
- B - Efficiency Evaluation
- C - Resource Efficient Process Chains

As seen by the framework, within each of these categories, steps have been provided to follow in order to essentially produce the most resource efficient process chain. The first step includes the ‘*Part and Process Design*’ for the manufacture of the Titanium component. As with framework V₁, the process chain rationale and the design for AM, SM and combination process is first considered. Once the user has decided which designs for the process can be utilised, he/she can identify the batch size of the build, if support structures are needed, the enhanced functionality of the build and the potential for material waste reduction. From here suitable process chains for the manufacture of the specific component are able to be developed and considered, leading onto the next step, ‘*Process Planning*’. As described in Chapter 5, the possible manufacturing process chains will then need to be examined in terms of the capability of the different Titanium manufacturing machines together with



the machine profile. The human factor also forms a major part of the process planning as material waste in form of defects and thus resource efficiency is greatly affected by it.

Once this has been attained to, the following step is the '*Process Qualification*' which falls into the Efficiency Evaluation category. The key factors effecting resource efficiency are listed and thus need to be calculated in order to determine the most resource efficient process chain for the manufacture of Titanium and developed Titanium components. CAM software together with previous studies is able to be used in this evaluation process in order to compare and determine the most resource efficient process chain. Once these key factors of resource efficiency have been accounted for, a final process chain resource efficient process chain is determined.

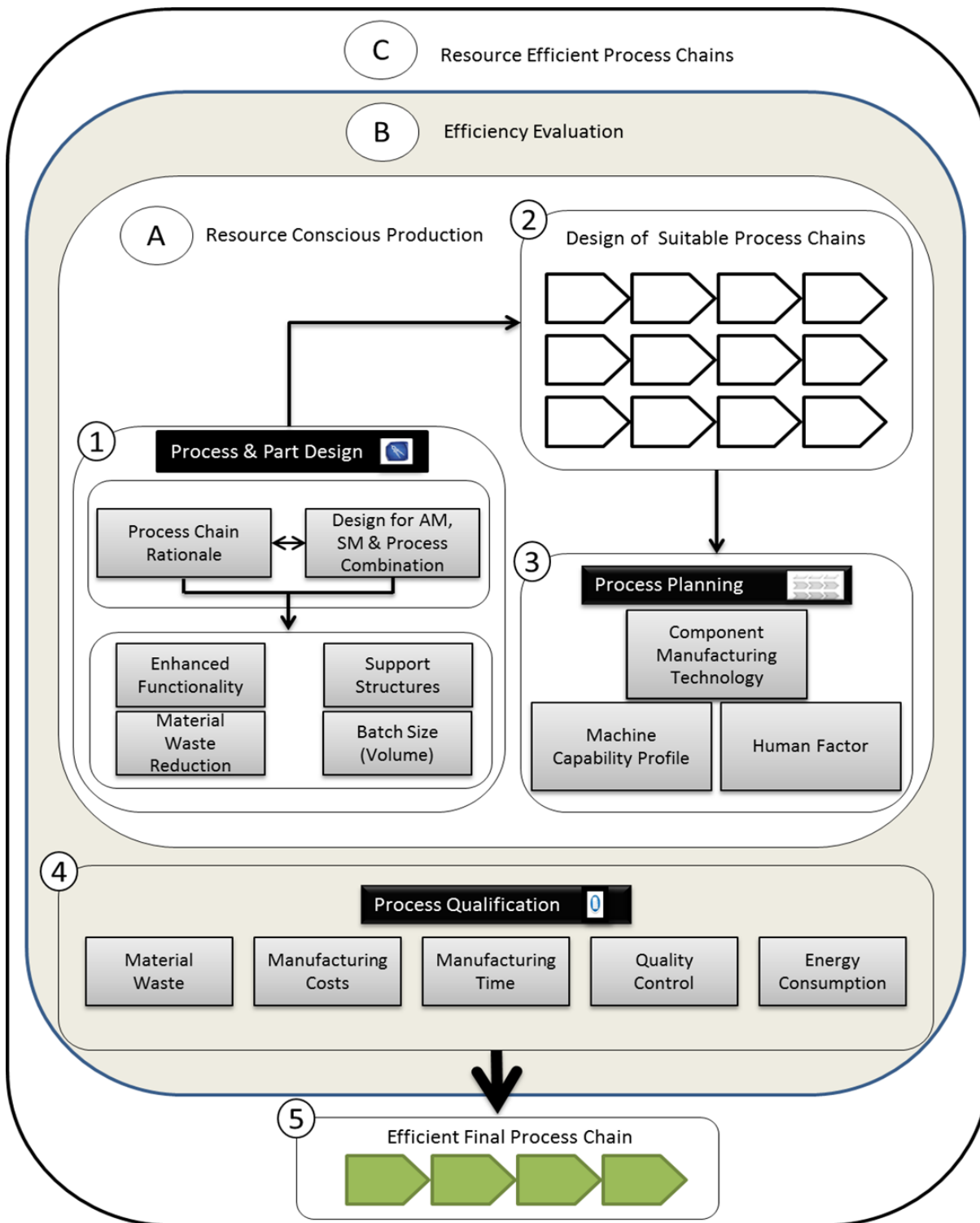


Figure 39: Developed Framework V₂



6.3 Component Build and Results

For the manufacture of the Banana Brace aerospace component, when compared to the traditional process using machining of a cuboid billet, several other processes variations were able to be deliberated. Other processes for the manufacture of the Banana Brace were considered such as producing the part using a round profile cuboid billet, followed by bending of the billet and then machining. Another process considered was the flattening of the round billet, followed by bending and extrusion. However before manufacturing of the component commenced, it was realised that both process chain were subsequently not going to form part of a resource efficient production. That being said, it gave the ability to investigate the resource efficiency of using an alternative process chain apart from the traditional, purely subtractive machining process. The alternative process chain to be evaluated was to use a smaller titanium billet that would essentially be bent into the curved geometry required for the part and following this, machined into the final geometry and features for the component. The two different designed process chains that will be evaluated for resource efficiency can be seen in the Figure 40 below.

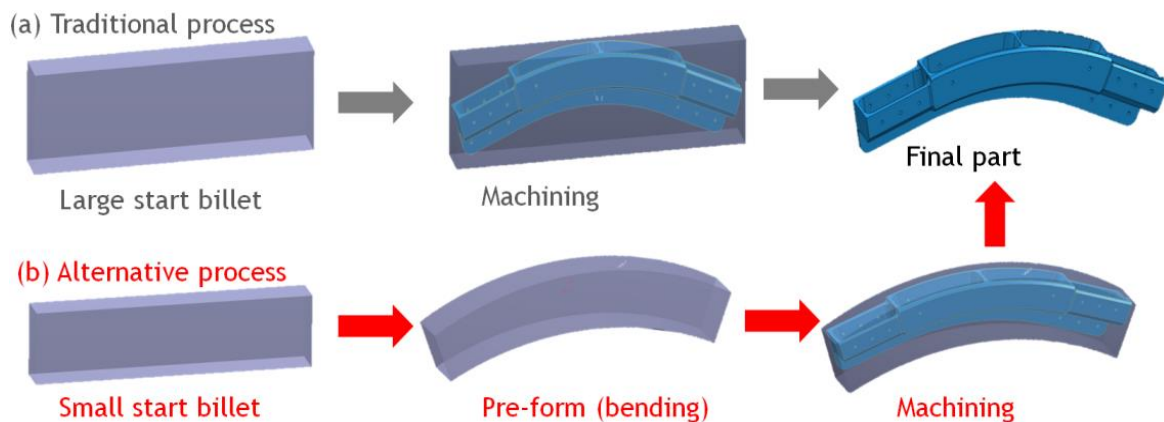


Figure 40: Two different process chains used to develop the banana brace ; (a) the purely subtractive process; (b) process combination - forming and machining

In order to bend the Titanium billet, a pre-heating procedure was required. As mentioned in Chapter 2, Titanium becomes brittle at a temperature of roughly 980⁰C, thus the billet was heated to 960⁰C in order to enhance the ductility of the billet. The forming setup for this process can be seen in Appendix C.

The subtractive processes used in both process chains involved the 5-Axis CNC Milling machine in which a CEA (constant engagement angle) was utilised of the roughing of the component. Especially in the manufacture of Titanium this is extremely important as high forces and temperatures used in cutting operations have extremely harsh effects on the tool life. With regards to the finishing operations, surface and swarf milling of the



component was performed. The strategies and cutting parameters were optimised from previous titanium builds in order to improve the surface finish and the tool life and are summarised in Appendix D.

Still focusing on the design of the process chains, three setups for machining were used within the two different process chains as illustrated in the Figure 41. For the purely subtractive process, the first setup was used in order to remove most of the material from the billet in order to get a shape close to the pre-formed part (near net shape). The second and third setups were then used in order to machine the material away from the features with the use of two different machining orientations. When using the alternate process chain, the billet was bent in order to develop the pre-formed part and then machined respectively. The setups and process chains for both procedures can be seen in Figure 41 below. The reasons why the tool-paths were created was so that there were only two extra roughing operations needed for the purely subtractive process so that both parts could start the machining operations with similar geometries. For the rest of the cutting processes, the same procedures were used. The cutting parameters together with the experimental equipment used in the process chains can also found in Appendix D.

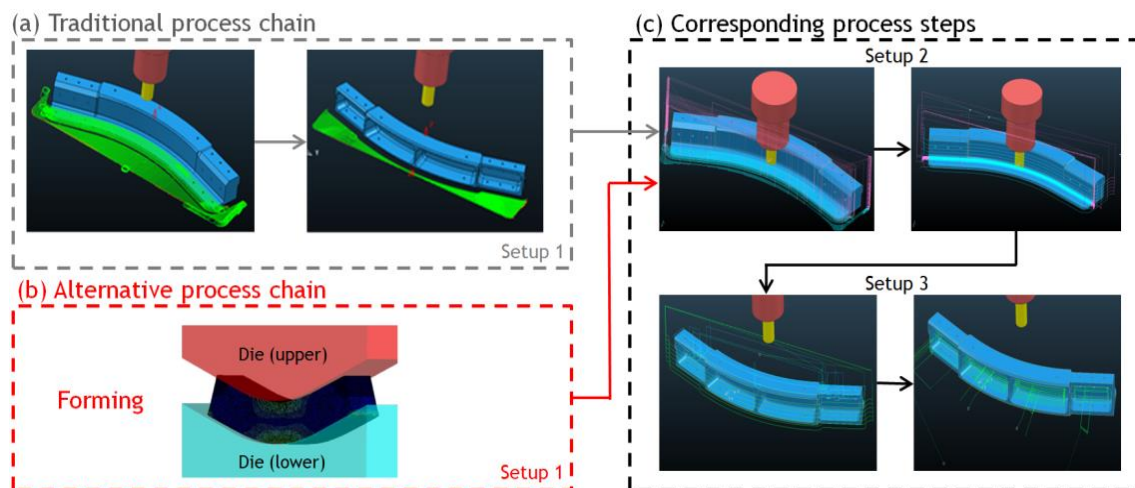


Figure 41: Comparison of the Process Chains; (a) traditional process chain; (b) alternative process chain; (c) final manufacturing steps for both processes

For the purely subtractive process, a titanium billet of 32.66mm x 86mm x 291mm was used for the manufacture, having a total volume of 816cm³. Upon completion of the traditional CNC machining process, the Banana Brace had a volume of 124cm³, thus incurring a figure of 84% volume removal and 693cm³ of material waste. The costs of the production and the machining time for the purely subtractive process are summarised in the following Table 19.

**Table 19: Manufacturing Time and Costs for the purely subtractive process**

Application	Tool life factor	Unit price	Quantity	Total
Billet	-	R 1000 / kg	3.6 kg	R 3615
End mill (dia. 10 mm)	0.3	R 1360	1	R 408
End mill (dia. 12 mm)	0.5	R 1710	1	R 855
End mill (dia. 16 mm)	1	R 2580	1	R 2580
Setup	-	R 700 / hr	30 min	R 350
Machining time (roughing)	-	R 700 / hr	132 min	R 1540
Machining time (finishing)	-	R 700 / hr	72 min	R 840
Total				R 10188

For the alternative process involving the forming followed by the milling, a smaller Titanium billet was used as it could be bent into the pre-formed shape required. In order to determine the smallest billet possible, test runs were performed in order to illustrate the smallest billet size capable of being used without affecting the final outcome of the Banana Brace component. From these trials, the billet size was reduced from dimensions of 41mm x 57.5mm x 301mm with a volume of 709.6cm³ to dimensions and a volume of 36mm x 56 mm x 291mm and 586.7cm³, resulting in a 17% material saving. When compared to the purely subtractive process, the amount of material saved was as high as 28%. The machining steps and setups for the alternative process can be seen in the figure below.

Due to the pre-form shape of the Banana Brace having an awkward shape, the first setup was used to machine the billet into different orientation planes. This setup would allow for positional referencing in the future setups. The second setup was used to remove material from the outside flange with the last setup being used to remove the material from the pockets. The manufacturing costs and times for the production of the alternative process can be seen in Table 20.

**Table 20: Manufacturing time and costs for process chain combination**

Application	Tool life factor	Unit price	Quantity	Total
Billet	-	R 1000 / kg	2.6 kg	R 2598
Preform process	-	R1750 / hr	60 min	R 1750
End mill (dia. 10 mm)	0.3	R 1360	1	R 408
End mill (dia. 12 mm)	0.5	R 1710	1	R 855
End mill (dia. 16 mm)	0.7	R 2580	1	R 1677
Setup	-	R 700 / hr	60 min	R 700
Machining time (roughing)	-	R 700 / hr	98 min	R 1143
Machining time (finishing)	-	R 700 / hr	72 min	R 840
Total				R 9971

As seen by the results, the combination process incurred high machining and manufacturing time when compared to the traditional process. This is due to the fact that the pre-formed shape had to have a more complex machine setup. That being said though, due the billet being smaller, roughing time as well as tool life were reduced which resulted in lower costs. The manufacturing time for the alternative process was 13% longer than the traditional process. When evaluating the cost, the additional costs of the forming process cancels out most of the cost savers such as material, machining times and tool life for the process combination. The manufacturing cost for the process combination is thus only reduced by 4% when compared to the traditional process.

The quality of the final components was also measured using an accuracy comparison to the traditional CNC design. A CMM machine was used to compare the two parts. As seen in Figure 42, the error distribution of the attained brace was a value of 0.007mm with the maximum deviation of 0.11mm being recorded around the outer edges. The deviations of both components were well within the specified aerospace parameter range and thus the quality was up to standard.

From the results, it shows that the resource efficiency of using the combination process did not improve as significantly as was previously thought.

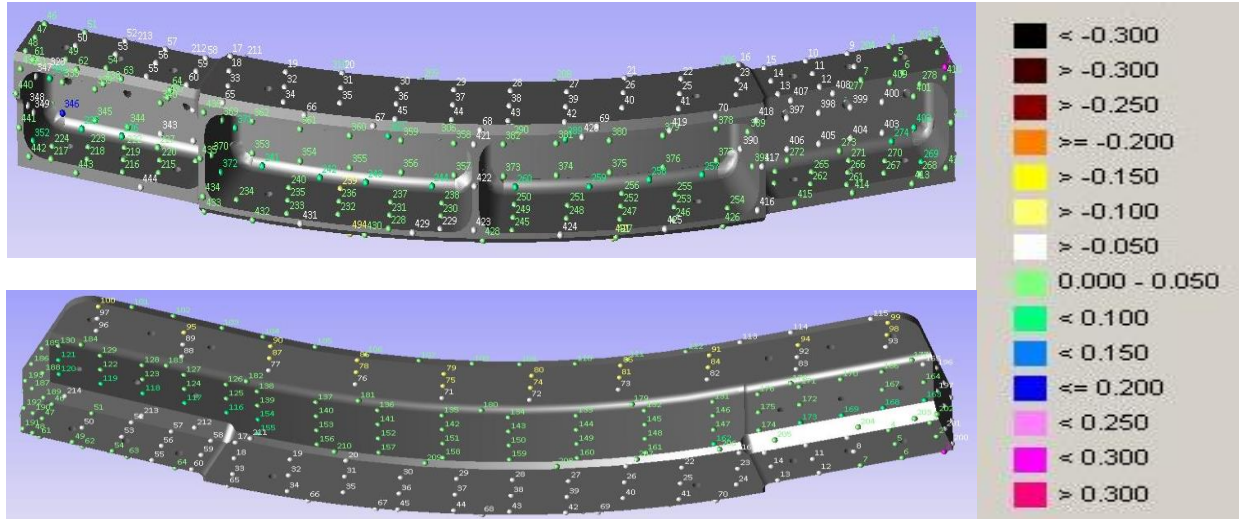


Figure 42: Comparison of the accuracy of the combination process using CMM

6.4 Framework Validation

The manufacture of the banana brace aerospace component proved to be that of a resource efficient process as both process chains used were of similar efficiency. With regards to the V₂, the framework proved to be developed enough in order to investigate the resource efficiency of the manufactured titanium component. With specific reference to the framework, the key factors and aspects of processing titanium components were evaluated and run through in order to determine the most resource efficient process chain. As with the previous two frameworks, a qualitative assessment of the V_{Final} was performed by the manufacturing specialist. The assessment was performed with the same scoring procedure with regards to the manufacturing process. The assessments are shown in Figure 43 and summarised in Table 21 below.

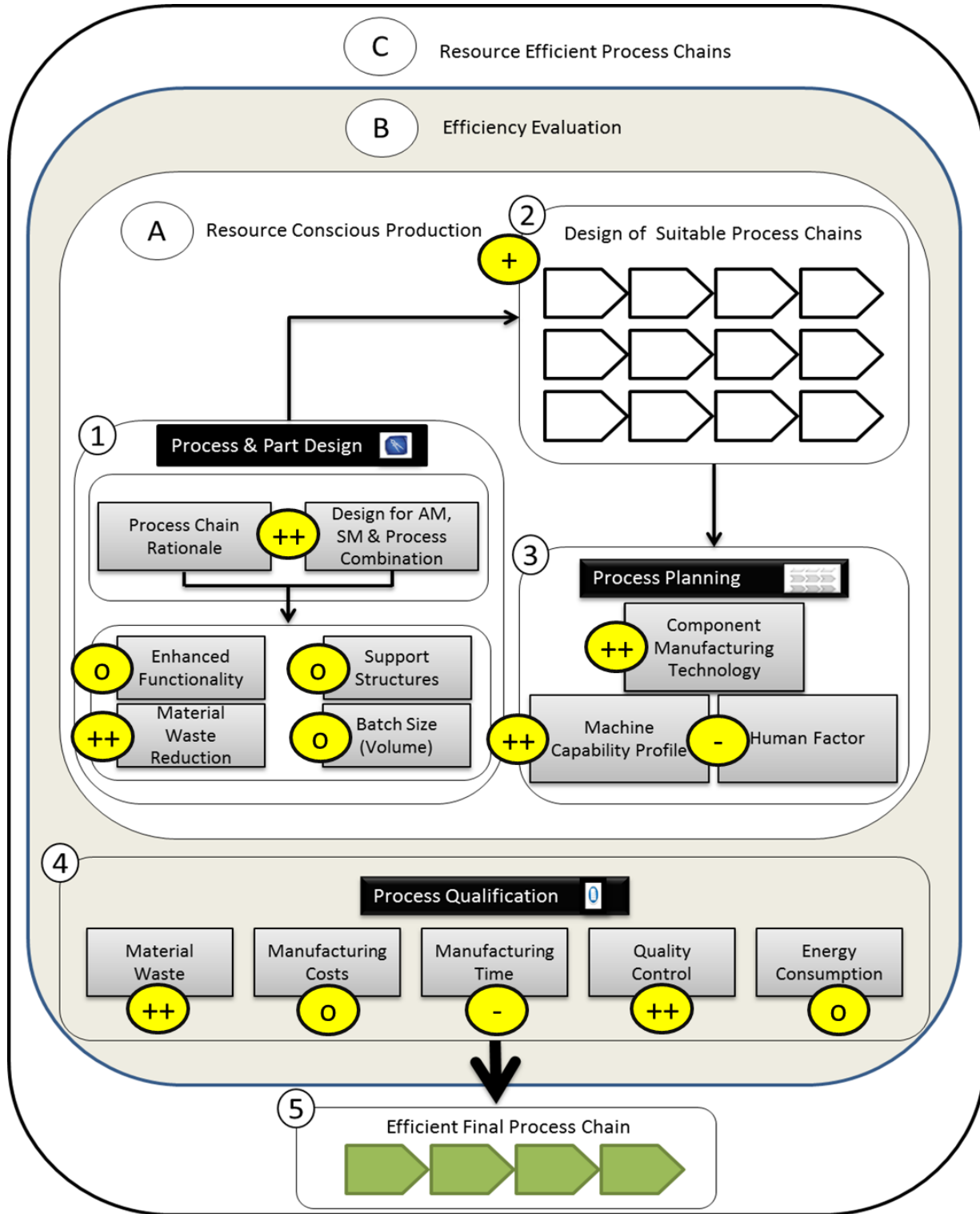


Figure 43: Qualitative assessment of framework V₂ (+++...very good, ++... good, 0...neutral, -...poor,---...very poor)

**Table 21: Summary of Qualitative Assessment**

A: Resource Conscious Production			B: Efficiency Evaluation		
1. Process & Part Design		2. Process Planning		3. Process Qualification	
Design for AM,SM and Process Combination	++	Component Manufacturing Technology	++	Quality Control	++
Enhanced Functionality	o	Machine Capability Profile	++	Material Waste	++
Material Waste Reduction	++	Human Factor	-	Manufacturing Cost	o
Support Structures	o			Manufacturing Time	-
Batch size	o			Energy Consumption	o

6.4.1 Resource Conscious Production

The category of the framework utilising Resource Conscious Production included both the ‘*Process and Part Design*’ and the ‘*Process Planning*’ sections. Due to the nature of the manufacture, design for the Process Chains was fully considered for the development of the banana brace hence the good score. For the reason that enhanced functionality specifically refers to AM processes, a neutral score was given due to no need for AM to be used together with the support structures and batch size as only one component needed to be manufactured for each process. A large amount of focus was set on the material waste reduction aspect of the build as a new manufacturing method was designed in order to use a less Titanium.

After the suitable process chains have been designed, the framework moves onto the ‘*Process Planning*’ section. Forming part of this assessment section, evaluation of the machine capability profile, as well as the titanium manufacturing machine proved that they were more than sufficient to use for the specific design of the component together with the specific design of the different process chains, yielding high validation scoring. Due to the inability to use standard fixturing for the pre-form shape, the human factor resulted in a poor rating as the new design features for additional clamping had to be taken into account, which caused confusion between the manufacturers.

6.4.2 Efficiency Evaluation

The efficiency evaluation understandably included the ‘*Process Qualification*’ section as this determines the outcome efficiency of the process chain. The quality was determined by the accuracy of the part using the CMM



machine and was within the aerospace tolerance range. Material waste of the combination process was as much as 28% material saved, hence the good rating. With regards to the manufacturing cost, both processes attained similar findings as additional costs were needed for the additional forming process. Time was also counteracted in this case as although a 2% saving in machining time was seen, the pre-form process led to a 13% longer manufacture time. Exact energy consumption for the processes could not be calculated as there were constant deviations in the working engagement (a_e) and cutting depth (a_p) hence the neutral score.

6.4.3 Shortcomings and possible changes to Framework V₂

As seen from the results and validation of the framework, the resource efficiency of the developed Titanium component could be investigated through the various factors mentioned and thus the framework can be used and implemented into a useful tool. The final input of the Framework will first be the incorporation of the 6R concept (refer to Chapter 2) followed by the Excel tool developed to determine the most resource efficient process chain by analysing and evaluating the key factors of the *Process Qualification*. The final framework, V_{Final}, is illustrated in Figure 46 below.

6.5 Incorporation of the Framework into the 6R Life Cycle

In order to fully approach manufacturing with resource conscious production and sustainable manufacturing in mind, one has to look at the titanium manufacturing product life cycle (PDC). By analysing the product life cycle, it is easily understandable that the V_{Final} framework is able to incorporate itself into the Life Cycle through the 'Product/Process Design' and the 'Manufacturing' steps essentially (refer to Figure 44).

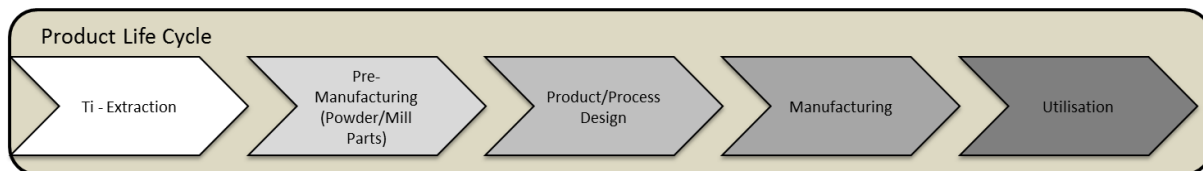


Figure 44: Titanium Product Life Cycle

That being said, understanding the way in which the 6R's of manufacturing are utilised through literature, they are able to be incorporated into the life cycle like so:

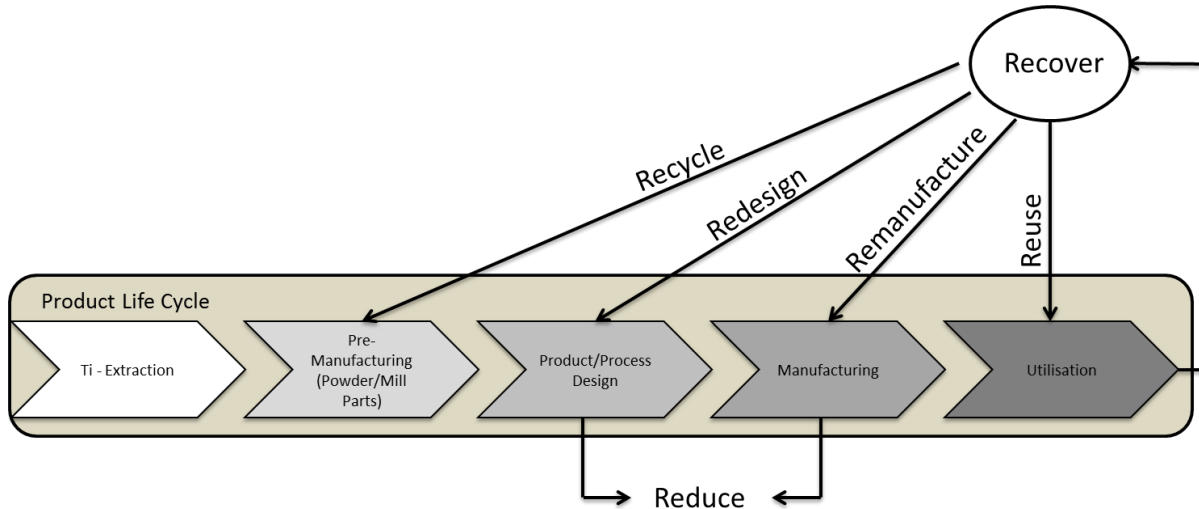


Figure 45: 6R incorporation to the Titanium Product Life Cycle

By following this process, the final Framework incorporating the titanium product life cycle, both resource conscious process chain production and sustainable manufacturing was able to be developed and is illustrated through Figure 47.

Included together with the V_{Final} framework is a constructed template which both manufacturers and users can utilise in order to fully understand and follow the framework. The template was designed in order to assist manufacturers and possible new manufacturers that are still unsure of how to develop components that are value adding and at the same time resource efficient.

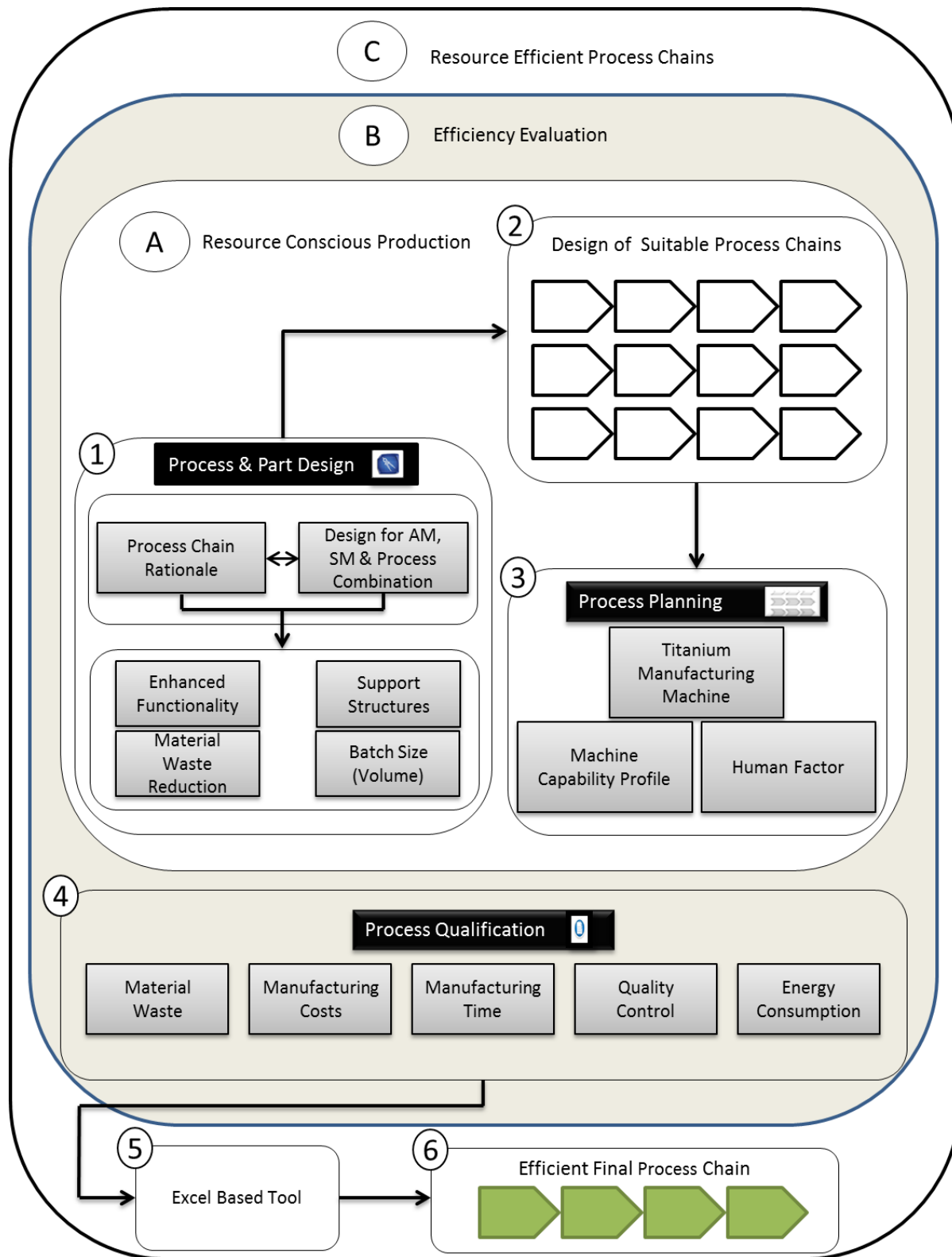


Figure 46: Final Framework used for investing resource efficiency

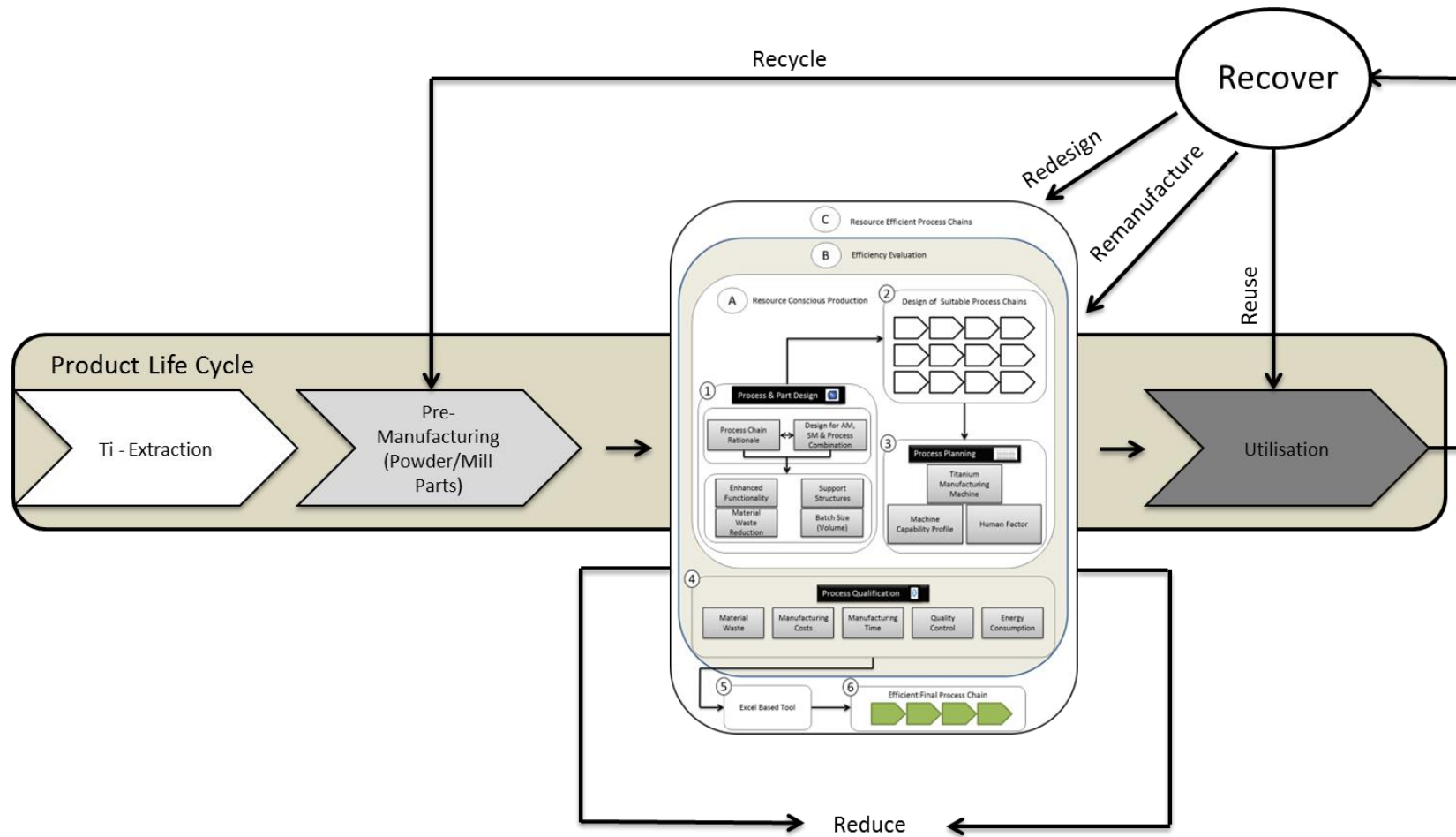


Figure 47: Resource Efficient and Sustainable Framework Incorporated into the Titanium Product Life Cycle



7. Framework to Excel Based Practical Tool

The following chapter discusses the way in which the framework V_{Final} is used to a full extent in order to investigate the resource efficiency of different process chains in titanium manufacturing through a developed in house excel tool in VBA (Visual Basic for Applications) [139].

7.1 Excel Tool User Interface

An important feature to consider in the design and development of any developed tool that will be possibly used is the level of user-friendliness and practicality. That being said, the excel tool has been developed in order for first time users to understand and to assist manufacturers with a clear set of instructions on each userform. The layout of the tool was developed into a logical flow where users are able to select and quantify the requirements or factors of the process chains they require to evaluate. Due to the nature of the model, it can essentially be used for any type of process chain, however, for this study, it was purely used for investigating the resource efficiency of process chains used to manufacture titanium components.

When the user opens of the excel tool, userform1 appears, as illustrated through Figure 48. Accompanying the userform are a set of insert fields in which the user is able to input the identified key factors he/she wishes to evaluate in the process chain together with the unit of measurement, for example if the factor the user wants to evaluate is time, the unit will be minutes. Once the first evaluation requirement is chosen, the user has to decide the degree of importance and the utility of the identified factor. So if the user feels that that specific requirement in the process chain is more value adding to resource efficiency than another factor, a higher percentage rating will be given. Another illustration of how the user can decide on the weighting criteria is that if he/she is trying to manufacturing a large batch of components in the smallest about of time possible, time will be regarded as the major factor affecting the efficiency of the process and thus need a higher weighting than the rest of the input factors. These weighting percentages of the factors undergoing investigation have to add up to a total of 100% which is shown in the Total Percentage orange bar below after each factor is input. On completion of the 100%, the user can select continue in order to move to the next evaluation step.

The second userform (Figure 49) gives the user a chance to insert the various process chains that he/she wants to evaluate. When faced with userform2, the first step of the user is to select 'Add a New Process Chain'. Following this, the tool gives the user the option to name the process chain and then add the process to the program through the 'Add Process' option. For the user to continue uploading process chains, they should again select 'Add New Process Chain' until the required process chains for evaluation have all been uploaded and the user satisfied. From here they can move onto userforms3 by selecting the 'Insert Data' option.



Insert Box

Determining Resource Efficient Process Chains

Please insert your Key Factors from the Process Qualification Step in the Framework

These Factors are without value

Insert Process Qualification Factor Unit

Material Waste mg

Insert Factors Degree of Importance

30 %

Insert Continue

Total Percentage 0%

Figure 48: Userform 1 of the Excel Tool

Insert Process Chains

1. Add a new process chain
2. Enter Process Chain name
3. Add Process
4. After inputting all your chains select the "Insert Data" option

Add new Process Chain

Process Name

SLM & CNC

Add process

Insert Data

Figure 49: Userform 2 of the Excel Tool



Userform3 as presented in Figure 50, gives the user the chance to provide the data collected for the various process chains. The programme begins with the first process chain previously input by the user. The user then is able to input the data of the various key factors he/she is evaluating, as they identified in userform1. The user should select the ‘*Insert*’ option in order to upload the values to the tool. Once the user has completed uploading the data for the first process chain, the programme will move from row to row until all required fields needed for the evaluation of the process chains have been completed. The user is then advised to select ‘*Continue*’.

The image shows a software window titled "Data gathering" with a close button (X) in the top right corner. Inside the window, there are three input fields arranged horizontally. The first field is labeled "Total Chain1" and contains the number "40". The second field is labeled "Material Waste" and is currently empty. Below these fields are two buttons: "insert" and "Continue".

Figure 50: Userform used to input evaluation data

Figure 51 illustrates userform4. Here, a dropdown list is provided listing the factors identified in the first userform. Once a factor is selected, a lower and upper limit is required to be input. The lower limit input figure essentially determines that which the manufacturer thinks is not a resource efficient value for that specific factor whereas the upper limit determines the vice versa, what the manufacturer would think is a resource efficient value for that specific factor of the process chain. That being said however, the range of the upper and lower limit needs to incorporate the previous inserted data. For example, if the material waste of the process was 30mg, then a lower limit could be 40mg meaning that won't be resource efficient and an upper limit could be 28mg, stating that would be resource efficient for the manufacture. Each time the user has completed a limit, he/she should select ‘*Save the references or goals*’ and then add the input of the next factor.



Figure 51: Userform used to reference the limits of the data

From here, the Excel method evaluates the different process chains through the upper and lower limits given. The difference between the bounds gets divided between equal parts with regards to the previously input key factor data. The upper and lower limits are then distributed between ten equal intervals. These intervals are calculated as follows:

$$Interval = \frac{(Upper\ Limit - Lower\ Limit)}{(Interval\ length - 1)} \quad (11)$$

From here a function within the VBA searches through the interval data, comparing the different interval values to the data values the user input to the process chains. The function then sends back a score rating between one and ten, depending on where the actual data value lies between the interval values. Each data value for the relevant associating factor is then measured and scored. Once scored, the values are multiplied by the corresponding weighting presented in userform1. Following this, the results are finally added until the two process chains have a calculated total score. On completion the user can select 'Show Results', where the excel program outputs a comparison of the chains in bar graph form, showing the user which is essentially the most resource efficient process chains for their specific purpose. The final userform can be seen in the accompanying Figure 52.

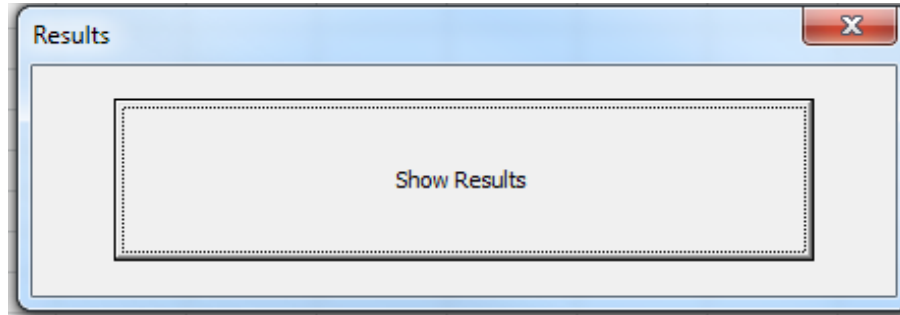


Figure 52: Final userform for the process evaluation

7.2 *Excel Model Validation*

In order to validate the created VBA Excel model and show the functionality of the program, the results of the manufacture of the three benchmark components will be used. The results will be used in order to demonstrate the tools effectiveness in its ability to compare the various process chains resource efficiency.

7.2.1 **Excel Model Validation: Intelligent Implant**

The following results were yielded from the Excel tool after using the data recorded for the Intelligent Implant manufacture. For the evaluation of the of the most resource efficient process chains, only three key factors were looked at. Namely the material waste, the cost and the time to manufacture. For each case, the three factors were of equal value to the resource efficiency assessment and thus each given a weighting percentage of 33.33%. As previously mentioned, this weighting criterion was multiplied to the interval values discussed. For the upper and lower limits, figures were looked at through our manufacturing specialists in order to determine what were 'good' and 'bad' values to acquire. The final output of the VBA excel tool is a bar graph, as seen in Figure 53, showing the different process chains and there process efficiency rating. As seen in the results concluded in Chapter 4, Process Chain 3 (Wire Cutting and CNC Combination Process) finished with a score of 7.01 and thus was declared the most resource efficient, followed by the SLM with a score of 6.3 and then the CNC machining process with a score of 5.99. The excel model program thus was able to confirm that this was indeed the most resource efficient process for single part production.



Score Process Chains

Process Chain 1	5.99
Process Chain 2	6.3
Process Chain 3	7.01

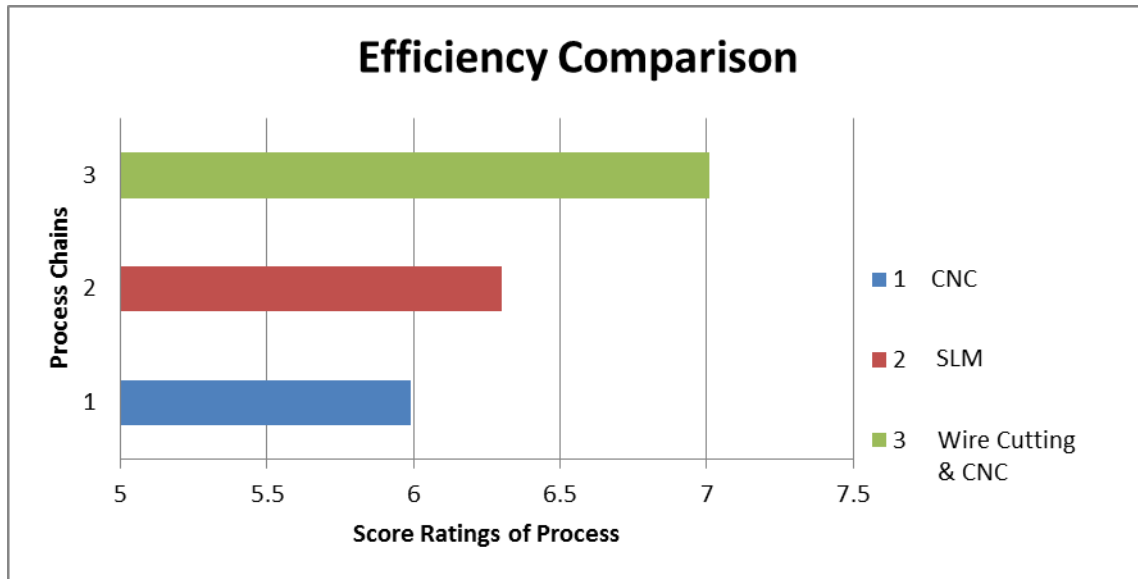


Figure 53: Bar graph showing the most resource efficient process chain between CNC, SLM and Wire Cutting and CNC

7.2.2 Excel Model Validation: Knuckleduster

The following results were yielded from the Excel tool after using the data recorded from the Knuckleduster manufacture. For the evaluation of the knuckleduster process chains, four of the key factors were looked at. These were the material waste, cost, time to manufacture and the quality (geometrical precision) of the components. Due to the fact that there were now four factors, a weighting percentage of 25% was given to each factor as they were all of equal importance to the resource efficiency evaluation. Again, for the upper and lower limits, figures were looked at through our manufacturing specialists in order to determine what were 'good' and 'bad' values to acquire. As illustrated in the bar graph in Figure 54 and as discussed and concluded in Chapter 5, process chain two involving the hybrid process of the CNC machining and SLM combination was the most resource efficient between the two process chains. The CNC and SLM process chain ended with a score of 5.25 through the calculated VBA whereas the CNC machining process alone ended with a score of 4.5 for the



resource efficiency of the chain. The excel model program thus again was able to confirm that this was indeed the most resource efficient process for single part production.

Score Process Chains

Process Chain 1	4.5
Process Chain 2	5.25

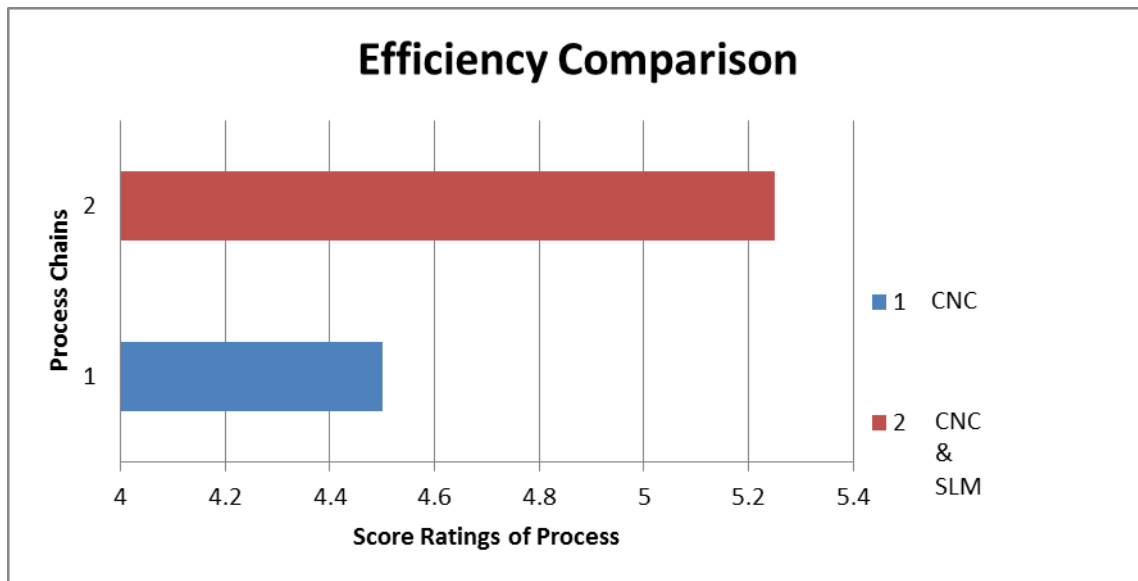


Figure 54: Bar graph showing the most resource efficient process chain between CNC machining and a combination of CNC machining and SLM

7.2.3 Excel Model Validation: Banana Brace

The following results were yielded from the Excel tool after using the data recorded from the Banana Brace manufacture. For the evaluation of the banana brace process chains, four of the key factors were also looked at. These were the same as for the knuckleduster: material waste, cost, time to manufacture and the quality (geometrical precision) of the components. Similarly to the knuckle duster component, a weighting percentage of 25% was given to each factor as they were all of equal importance to the resource efficiency evaluation. Again, for the upper and lower limits, figures were looked at through our manufacturing specialists in order to determine what were 'good' and 'bad' values to acquire. As illustrated in the bar graph in Figure 55 and as discussed and concluded in Chapter 6, process chain two involving the process combination of forming and CNC machining was the most resource efficient between the two process chains. The combination process chain ended with a score of 6 through the calculated VBA whereas the CNC machining process alone ended with a



score of 5.25 for the resource efficiency of the chain. Although when presented through the data it wasn't show such a large difference of resource efficiency, the tool was again validated correctly.

Score Process Chains

Process Chain 1	5.25
Process Chain 2	6

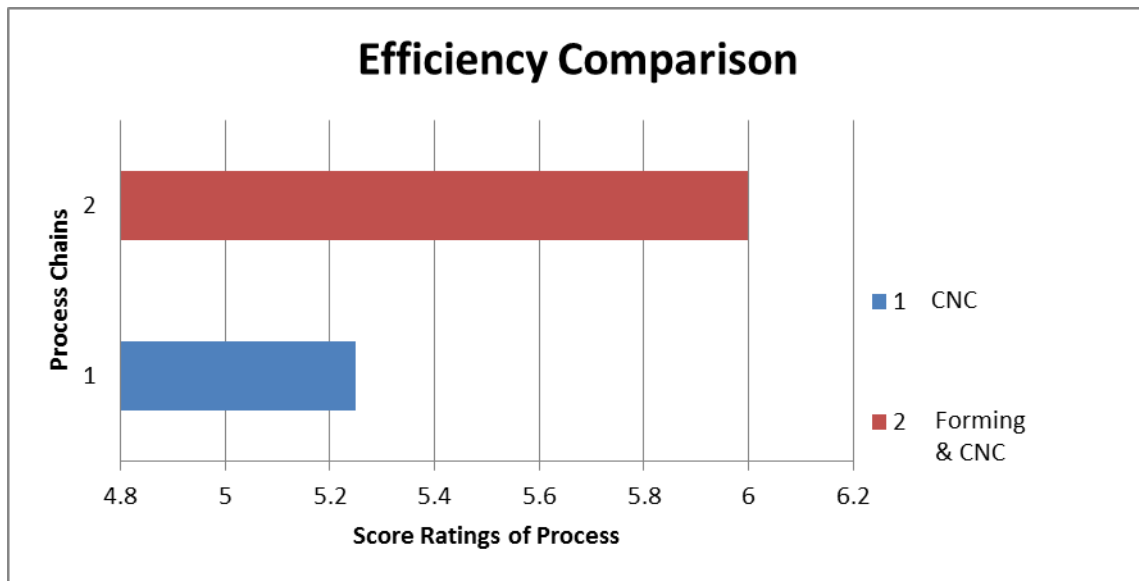


Figure 55: Bar graph showing the most resource efficient process chain between CNC machining and a combination of CNC machining and forming

7.2.4 Conclusion

The validation of the excel tool was presented in this chapter using the three titanium benchmark components discussed. As seen by the tool, it was successfully able to output the most resource efficient process chain when comparing the various processes input. It thus illustrated its ability to serve as a useful tool to manufacturers for both a pre- and post-process evaluation technique. This tool could possibly be utilised by the South African Titanium manufacturing industry in order to test different process chains in terms of what they require to be the most beneficial resource efficient factor. By using the tool, they could possibly apply their manufacturing on a wider scale if deemed resource efficient.



8. Conclusion and Future Work

The aim of this research was to develop a framework in order to investigate the resource efficiency of titanium manufacturing process chains. Currently the manufacturing scene in South Africa is highly turbulent where differences come from both from internal and external factors. In addition, the market and industry for titanium manufacturing is extremely competitive and producing a component and product through as little resources as possible while at the same time keeping the value of the component high, is highly beneficial and profitable but difficult.

Within the manufacturing industry of South Africa, there is both a lack of knowledge and competency for the manufacturing of titanium. There is too a limited amount of knowledge that is transferred between research institutions and the industry. Knowing this, it was understandable that there was no benchmark framework and template for the manufacturing of resource efficient titanium process chains. Further, there is no tool essentially able to assist manufacturers to measure resource efficiency both in a pre- and post-process sense. Hence the reason for this study, allowing manufacturers to have the correct, if not the optimal procedure to go about bringing resource efficiency and sustainability into their manufacturing.

Through the literature analysis, it was shown that there is a need for a framework to follow in order to achieve resource efficient titanium manufacturing. Even though there have been many different optimisation techniques that have been used and implemented over the years, a framework listing the main factors effecting resource efficiency did not exist together with an excel based tool. So far many of the techniques used to for resource efficient production are highly complex whereas by simply assessing other non-value adding activities, it will make manufacturing 'simpler'.

The original contribution from this study was to develop and validate a framework that can be used to investigate the resource efficiency of manufacturing titanium and that can also be possibly used in industry for manufacturers to perform resource conscious production and essentially limit their non-value adding factors. Further, in addition to the development of a framework, an excel based tool was developed that can be used both pre- and post-manufacture. This tool essentially outputs the most resource efficient process chain when comparing a series of different manufacturing strategies. The outcomes of both the framework together with the tool can assist manufacturers in:

- Assessing titanium manufacturing process chains
- Benchmarking a new developed process chain to an old one
- Identifying the key factors effecting resource efficiency



- Using the framework and model to potentially have a large resource saving together with sustaining the environment through the 6R concept of the framework

In order to achieve the framework, it was passed through a series of iterations. These iterations consisted of evaluating different industrial in-house experiments using various titanium benchmark components. Through these iterations, the framework was then able to be validated and refined with regards to the shortcomings known from the conducted surveys of the framework. The first iteration step consisted of the validation of the conceptual framework through the intelligent implant benchmark component. The different manufacturing process chains were evaluated through the conceptual framework by the manufacturing specialist, to which the framework was validated and scored/rated accordingly. Surveys were then conducted in order to determine the shortcomings of the framework. From here the framework was refined with specific reference to the shortcomings of the conceptual framework in order to develop framework V_1 . The second iteration followed the same procedure as mentioned above, except with a different benchmark component as well as the third iteration. A V_{Final} framework was then developed and constructed following the iterations through the various benchmark components, manufacturing specialists' analysis and the surveys.

Upon completion of the framework, the V_{Final} framework was then incorporated into the product life cycle of titanium components in order to integrate the 6R concept. This inclusion will give manufacturers and users the ability to produce titanium components both resource efficiently while simultaneously ensuring sustainable manufacturing. Together with the excel based tool, the framework will and can be essential in investigating future process chains and resource efficiency analyses regarding the manufacturing processes and the equipment/technologies needed for the process. By implementing the framework and excel tool, it can be used to successfully transfer knowledge on various process chain inputs and outputs together with assistance to a manufacturer's decision making for the purpose of adding value and minimising non-value adding procedures.

Toward a full industrialisation of the research, this initiative strives to make a direct contribution to the South African titanium manufacturing industry by allowing manufacturers to utilise the framework and tools provided so that their business and production lines can essentially become more sustainable and resource efficient, thus increasing the competitiveness of titanium manufacturing as a whole. This could possibly have the potential to position South Africa better globally for titanium resource efficiency and sustainability.

Future work associated with this research will involve further development and refinement of both the V_{Final} framework together with further development and refinement through the excel tool. With regards to the framework, extended research needs to be performed at an industry level in order to determine whether or not it is viable for manufacturers producing large batches and having large process chains. Development of the



framework in this study was only performed with titanium alloys. There exists potential to take the framework further and incorporate other materials such as tool steel, aluminium or carbide. With further development of both the framework and tool, they can be integrated fully into manufacturing companies for them to utilise in the production of new resource efficient, sustainable products.



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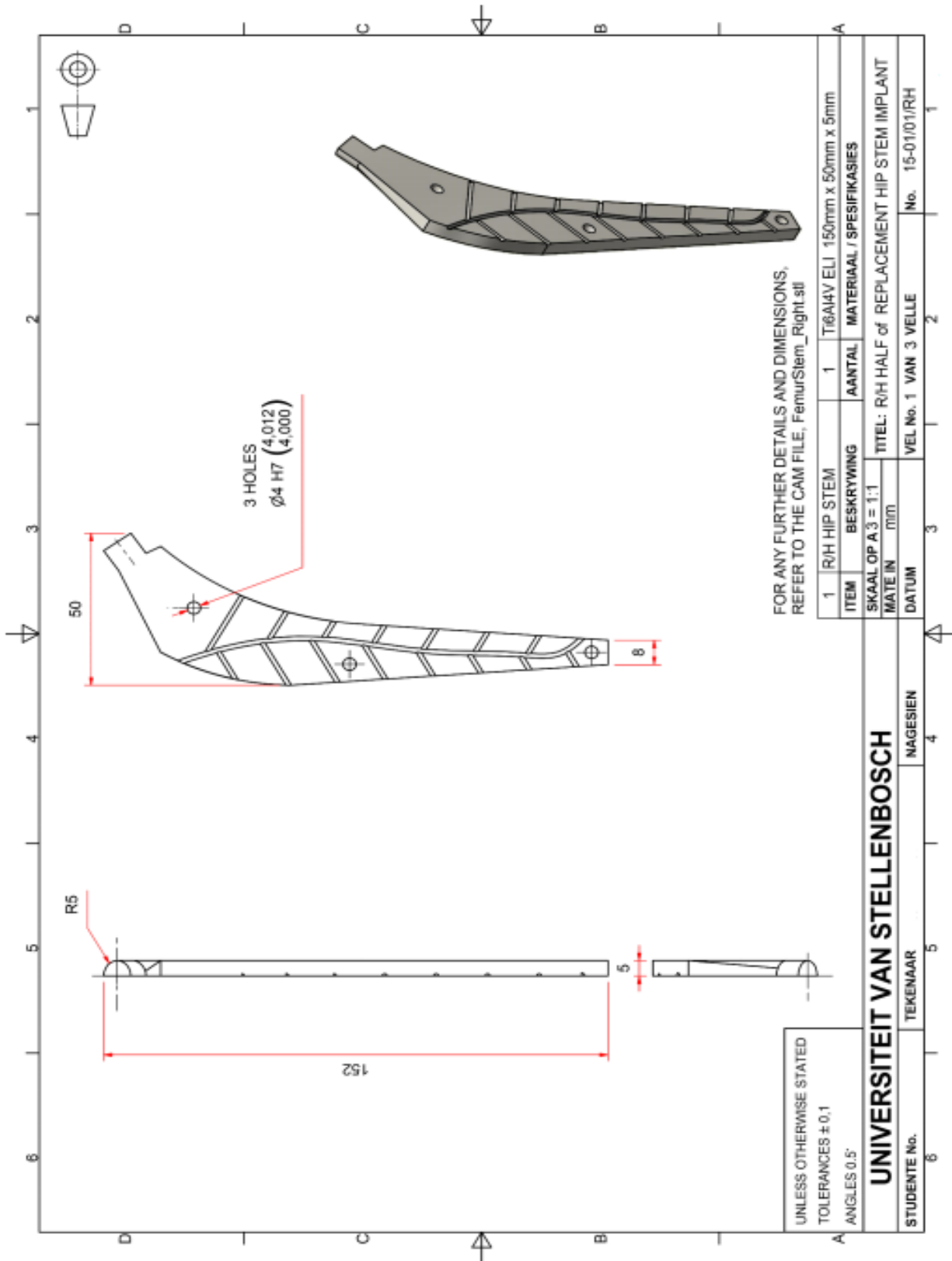


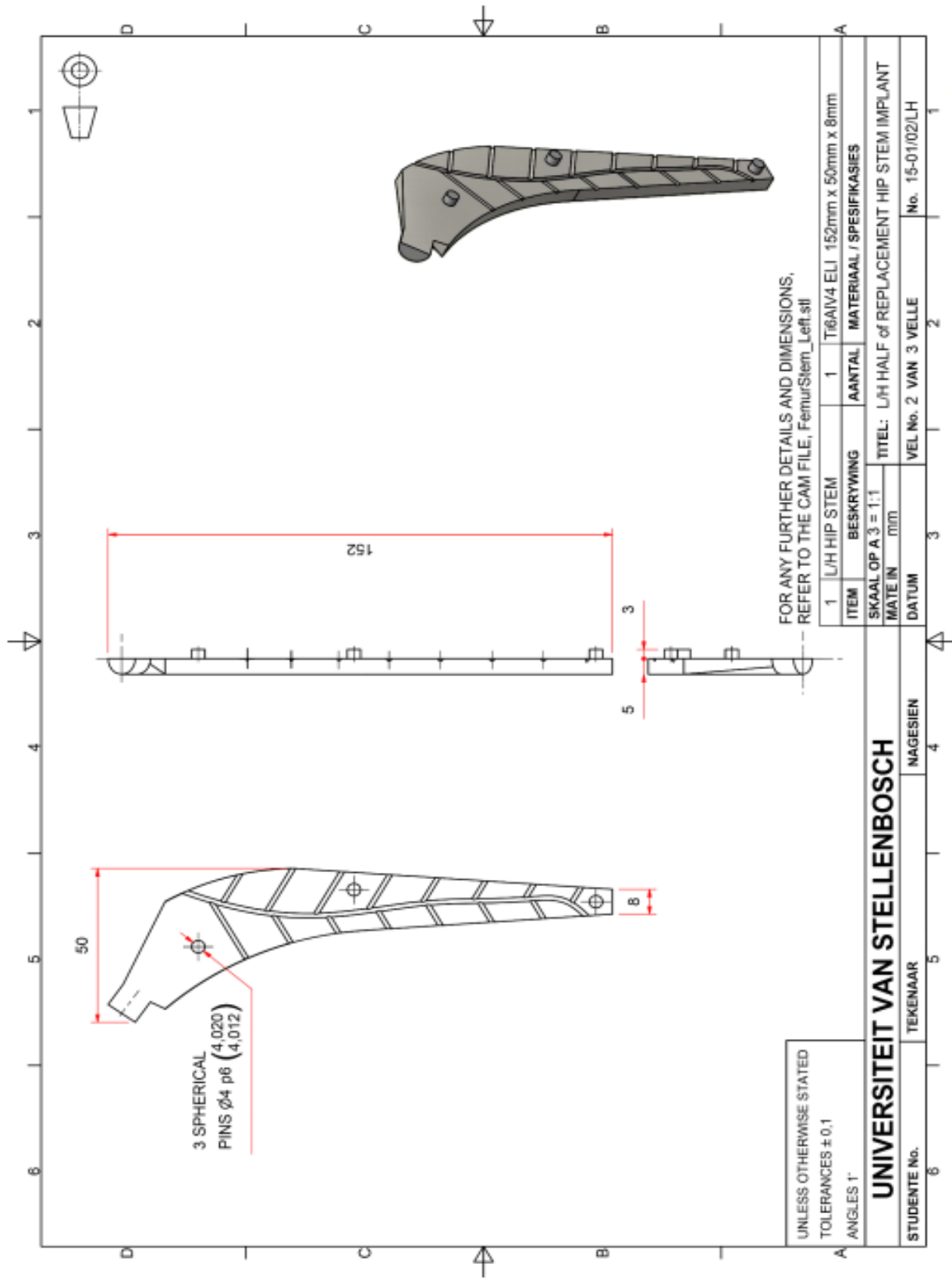
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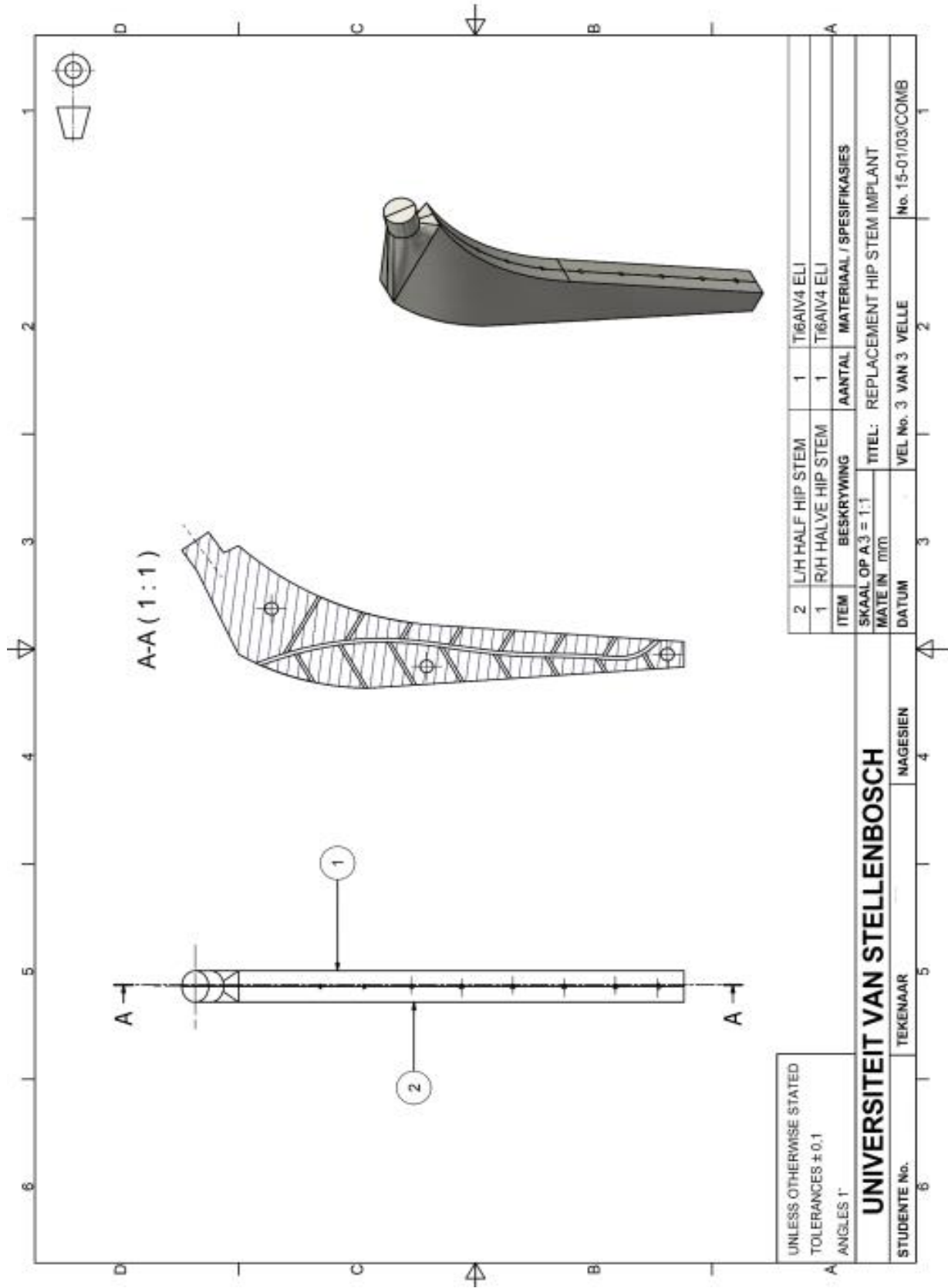


10. Appendix A: Design of the Implant

The following appendix shows the design drawings for the left and right hand sides of the hip implant. These designs were developed for the CNC machining strategy and the hybrid process using the Wire Cutting and CNC Machining technologies. The design allows for drug delivery channels integrated into the implant deeming it an ‘Intelligent Implant’.









11. Appendix B: Knuckle-Duster Titanium Component

The following Appendix illustrates the cutting parameters used for the CNC machining and the SLM process in developing the Knuckle-Duster Component. The tool paths for the component are also illustrated.

Table 22: CNC Machine Cutting Parameters

Cutting Parameters	Setup 1: Pockets	Setup 2: Pockets	Setup 2: Slot
N[rev/min]	2189	3503	12000
f_x[mm/tooth]	0.08	0.08	0.06
v_c[m/min]	110	110	226
F[mm/min]	1400	1681	2900
a_c[mm]	1	0.8	0.2
a_p[mm]	23	11	0.2

Table 23: SLM Process Parameters

Model Slicing Parameters		General Parameters		Laser Parameters	
Islands	5mmx5mm @ 45°	Extra Coating	300mm/s	Focus diam.	0.15mm
Beam. Comp	0.02mm	Coater(in process and manual)	50mm/s	Scan Speed	600mm/s
Slice Thickness	0.03mm	Coater Current	100%	Power	100W



12. Appendix C: DFM and DFA Guidelines

Table 24: DFA and DFM Guidelines (adapted) [139]

Guideline for DFM and DFA	Effective Result of Guideline
1. Minimise Component Number	<ul style="list-style-type: none"> • Reduction in assembly costs • Easier Disassembly • Reduction in work-in-process • Fewer connections means fewer defects
2. Utilise commercially available material	<ul style="list-style-type: none"> • Material Cost reduction • Order time for the material is reduced
3. Design for easy manufacturing of part	<ul style="list-style-type: none"> • Feasibility of near-net shape • Avoidance of surface finishing requirements
4. Tolerances should be within process capability range	<ul style="list-style-type: none"> • Additional processing such as finishing will be need if tolerances are ‘tighter’ than the process capability
5. Design fool-proof product for assembly	<ul style="list-style-type: none"> • One way assembly in order for the assembly to be unambiguous
6. Design for assembly ease	<ul style="list-style-type: none"> • Minimise fasteners • Design assembly by using base parts for component addition



13. Appendix D: Banana Brace Titanium Component

The following Appendix illustrates the forming and cutting parameters used for the manufacturing of the Knuckle Duster component.

Table 25: Setup and Parameters for the Forming Process

Setup	Parameters
Hydraulic Press	DUNKES HD315
Punch Velocity	20mm/s
Billet Temperature	960°C
Tool Temperature	20°C

Table 26: Cutting parameters and strategies

Cutting Operation	Strategy	a_p [mm]	f_z [mm/z]	a_e [mm]	v_c [m/min]
Roughing	CEA	5-35	0.178	1	75
	CEA	5-10	0.146	0.7	85
Finishing	Swarf Milling	3-5	0.16	0.3	80
	Surface Milling	50	0.1	0.1	50



14. *Appendix E: Ethics Clearance*



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Approval Notice New Application

26-Sep-2016
Girdwood, Richard RD

Proposal #: SU-HSD-003493

Title: Developing a Framework to Investigate the Resource Efficiency of Manufactured Titanium Components

Dear Mr Richard Girdwood,

Your **New Application** received on **13-Sep-2016**, was reviewed
Please note the following information about your approved research proposal:

Proposal Approval Period: **20-Sep-2016 -19-Sep-2019**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

Please remember to use your **proposal number** (SU-HSD-003493) on any documents or correspondence with the REC concerning your research proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The Committee will then consider the continuation of the project for a further year (if necessary).

This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for an external audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.

We wish you the best as you conduct your research.

If you have any questions or need further help, please contact the REC office at .

Included Documents:



DESC Report
REC: Humanities New Application

Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)



15. Appendix F: Framework Surveys

Questionnaire Survey: Framework V1

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No
2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary
3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)
4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Still needs templates and design requirements
5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
6R's of manufacturing (reduce, recycle, reuse, remanufacture etc...)
6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Quality
7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No
8. Please leave any recommendations or opinions for the framework in the comment field.
Show flow, integrate templates, integrate the 6R's, show the cause effect on each element



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
What about prt and process design, inputs to process planning, process qualification

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Model should be generic, flow is not clear, machines only for titanium do not exist

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
What's the limit for the system, technology and process level? The limits for titanium manufacturing?

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.
Bring in the resource efficiency scope, what are the limits for material?



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Should have bigger life cycle (6R)

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Frameworks should build on theoretical frameworks

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.
Should link to the framework, 6 sigma, lean manufacture, 6r's



Questionnaire Survey: Framework V1

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Yes if properly structured

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Main factors shown but nothing further

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.
No guidelines



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
To a certain extent

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.
Framework is focused to much on AM



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.
Still to focused on AM, framework needs an explanation, feedback loops for 6R



Questionnaire Survey: Framework V1

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Quality, Why AM?, Design for AM

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Post processes, functionality, mechanical properties

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
I don't know all the factors

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
I don't know everything to do

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No
To an extent but spectrum is too large to comment

8. Please leave any recommendations or opinions for the framework in the comment field.
Questions too vague, sample size



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No
2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary
3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)
4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Feedback?
5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Don't know but it should help
6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Don't know everything
7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No
To an extent probably
8. Please leave any recommendations or opinions for the framework in the comment field.
Feedback, quality, life cycle, disposable, DMAIC, PDCA, lean manufacturing?



Questionnaire Survey: Framework V1

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Yes its applicable for the materials part of titanium

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
There may be

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

Yes the framework is useful however there might need to be more aspects on the qualification side

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

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 - No, a template is not necessary

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 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

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 - Yes
 - Kind of
 - Very Roughly
 - No

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 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
I don't understand how it works and its not clear

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Explanation at my first glance I don't understand

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Quality, design requirements, specifications

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Design suitable process chains has no explanation

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
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 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
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3. Is the framework user-friendly?
 - Yes (easy to use and follow)
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 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Unclear definitions

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Input data missing

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
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3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Needs refinement

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Unclear definitions of parts

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Missing input parameters

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
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 - No, a template is not necessary

3. Is the framework user-friendly?
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 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Needs to be more comprehensive form, part of the bigger picture, close the loop to the process

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
Product life cycle

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
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3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

Again more refinement

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

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 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
How do you measure or qualify/quantify the part complexity and part design

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Not sure how the user interfaces with part design

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

Framework is not clear on input side

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
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 - No (I don't understand the framework)

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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
 - Not sure

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Quality aspects

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

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 - Kind of
 - Very Roughly
 - No

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 - No (I don't understand the framework)

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 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

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 - Very Roughly
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 - No, these guidelines are irrelevant
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5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

I don't know everything to do with Ti manufacturing

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

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 - Yes
 - Kind of
 - Very Roughly
 - No

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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)
Quality

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
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 - No, a template is not necessary

3. Is the framework user-friendly?
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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V1

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 - Yes
 - Kind of
 - Very Roughly
 - No

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3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment
Yes upon understanding

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework V2

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

2. Does the framework require an explanation template for the user?
 - Yes, I don't know how to use
 - No, a template is not necessary

3. Is the framework user-friendly?
 - Yes (easy to use and follow)
 - Medium(unsure of some aspects)
 - No (I don't understand the framework)

4. Compared to your manufacturing strategy, do you think the framework could assist you in choosing the correct manufacturing process chain?
 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No
But probably not 'everything'

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



Questionnaire Survey: Framework VFinal

1. Do you understand the framework at first glance?
 - Yes
 - Kind of
 - Very Roughly
 - No

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 - Yes the guideline will help
 - No, these guidelines are irrelevant
 - Other, please comment

5. Does the framework assist you in designing resource efficient process chains?
 - Yes, the factors effecting resource efficiency are outlined
 - No there are still factors missing (please comment)

6. Does the framework incorporate everything to do with titanium manufacturing? (If No please comment)
 - Yes
 - No

7. Would the steps in the framework work for any manufacturing technology?
 - Yes
 - No

8. Please leave any recommendations or opinions for the framework in the comment field.



16. Appendix G: Framework Template

Titanium Manufacturing Template

V-Final Framework

The following template is served as a toolkit to assist users of the framework into a design driven thinking practice. The template outlines the various design outcomes presented in the framework and describes the different methods the manufacturers can go about in order to have a design centred thinking process for resource efficiency. The template should be populated where required.

Titanium Component:

A – Resource Conscious Production

1. Process and Part Design

Process Chain Rationale: Is the design process for the specific component justified? Are there specific customer requirements/product customisation needing to be accustomed for?

Design for AM, SM and Process Combination: What is the statistical Accuracy of machines? Are here preheating Procedures/Scanning Procedures? What is the envelope Size?

Enhanced Functionality: Are there possible performance cooling channels?

Material Waste Reduction: Ways in which waste reduction can be reduced through the process chain design?



Support Structures: Does the build require support structures? Are there ways to reduce the amount of support material?

Batch Size (Volume): How many parts are being manufactured? Possible build orientations for batch process in order to adhere to efficiency?

2. Design of Suitable Process Chains

Select from list of possible manufacturing technologies:

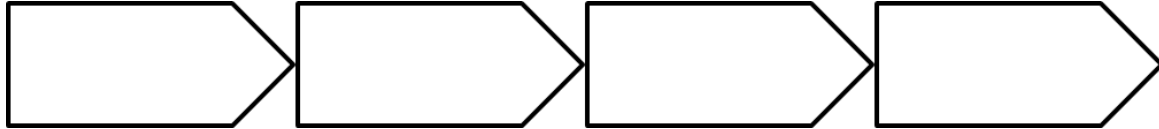
- i. Milling
- ii. Forging
- iii. Grinding
- iv. Plasma Coating
- v. Cutting
- vi. Additive Manufacturing
- vii. Sandcasting
- viii. Forming
- ix. Process Combination (Hybrid Process)

Process Number	Description of Build	Usable Manufacturing Technology
1		
2		
3		
4		
5		
6		

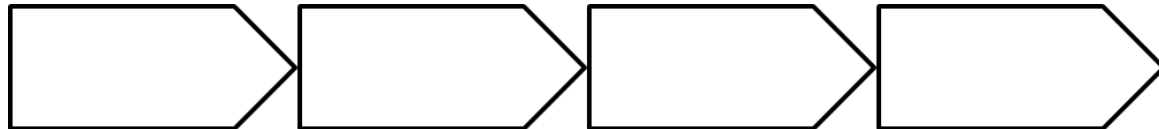


Design and the development of the Suitable Process Chains for the manufacturing of a Titanium Component.
Populate the chains with the process chain design: -

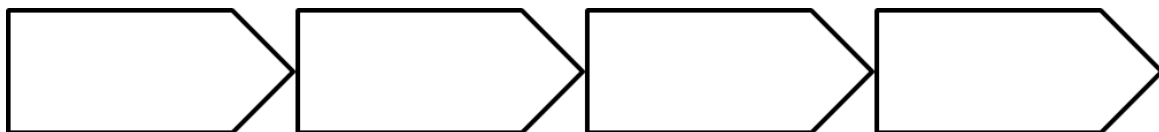
2.1



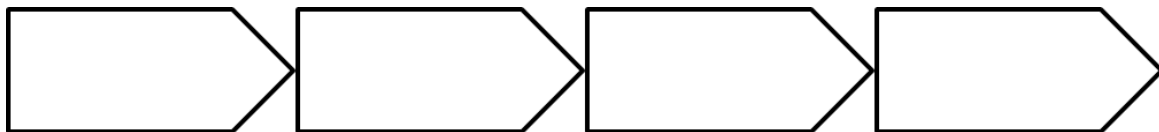
2.2



2.3



2.4



3. Process Planning

(Please see attached support documents for the process planning explanations)

Each suitable process chain design should be tested and populated.



Process Chain	Titanium Manufacturing Machine		Machine Capability Profile		Human Factor	
	Yes	No	Capable	Incapable	Experienced Personnel	Inexperienced Personnel
1						
2						
3						
4						
5						
6						

B -Efficiency Evaluation

Once the process chains have been thoroughly tested and worked through, the manufacturing of the component can begin. The data can be populated in the following table and captured throughout the manufacturing process. The data can also be populated through pre=operating processes such as CAM software and previous manufacturing studies.

4. Process Qualification

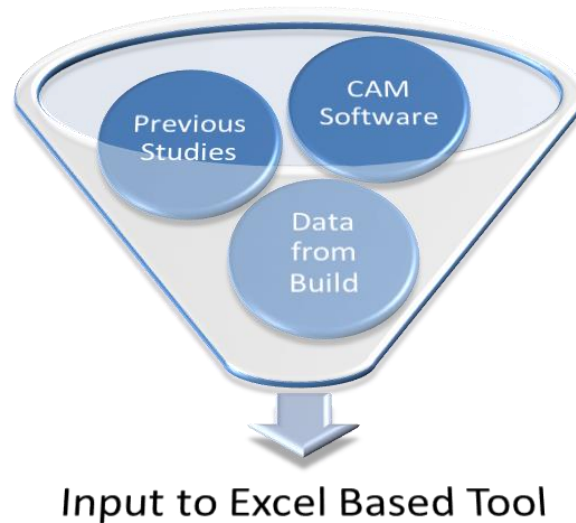
Process Chain	Material Waste	Manufacturing Costs	Manufacturing Time	Quality Control	Energy Consumption
1					
2					
3					
4					
5					
6					

C – Resource Efficient Process Chains

5. Excel Based Tool



Based on the above gathered data, the results can be uploaded to the excel programme in order to determine the resource efficiency of the different process chains., with a final comparison of efficiency between different compared process chains.



6. Efficient Final Process Chain

7. The 6R's of Manufacturing

Recover – Can the product being designed be post-used by either dismantling or disassembling it?

Reuse- Can the product be used again at its end of life?

Remanufacture-Are there techniques for new manufacturing processes to be used on the product post-life?

Redesign – Can the component be simplified in any way possible in terms of the design?

Recycle- Is there a way in which the product or the material of the product can be used for a new product?



Reduce- What actions or activities are there that when designing the component, are able to facilitate second hand use.