University of Pretoria

A Roadmap for the Titanium Metal Industry of South Africa

by

Nicolene Roux
10083589

Submitted in fulfilment of the requirements for the degree

PHILOSOPHIAE DOCTOR (Technology and Innovation Management)

in the

GRADUATE SCHOOL OF TECHNOLOGY MANAGEMENT
FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA
PRETORIA

Supervisors: Prof Elma Van der Lingen and Dr Anthon Botha

24 June 2020

I, **Rina Nicolene Roux** declare that:

the thesis, which I hereby submit for the degree at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

I have obtained, for the research described in this work, the applicable research ethics approval. I have observed the ethical standards required in terms of the University of Pretoria's Code of ethics for researchers and the Policy guidelines for responsible research.

Rina Nicolene Roux

Abstract

The South African titanium metal industry is underdeveloped and has a fragmented value chain. The aim of this study was to investigate fragmentation within the local titanium metal value chain by using industry technology roadmapping as a tool to comment on the completeness of each value chain stage. Roadmapping for the period 2021 to 2030 was applied to a novel value chain produced for the local titanium metal industry. Within the fragmented value chain, it was indicated that from the eight identified stages only four were established locally. The identified stages of the titanium metal value chain were: stage 1 - mineral reserves; stage 2 - slag; stage 3 – $TiCl_4$; stage 4 – sponge; stage 5 – melted products; stage 6 – mill products; stage 7 – metal powder production and stage 8 – metal powder products. Stages 1, 2, 6 and 8 are already established in South Africa.

The roadmapping type selected to address the fragmented South African titanium metal value chain was an industry technology roadmap. This type of roadmap focuses on forecasting the development, commercialisation and deployment of new technologies. The overall industry roadmap was designed using individual roadmaps for the value chain stages. These individual roadmaps were used as a guideline on what to include and what to exclude from the overall industry roadmap. The technology roadmap layout consisted of five layers namely market, product, technology, R&D, and resources. These roadmapping layers were applied to each stage of the titanium metal value chain resulting in the production of individual roadmaps for each stage. The roadmap model was based on the three fundamental questions in roadmapping: "Where are we now?" addressing the current state of each value chain stage, "Where do we want to go?" addressing the vision elements for each value chain stage and "How will we get there?" addressing how the vision elements would be achieved for each value chain stage.

The methodology used in this study relied on data collection from two main sources. The first was primary data collected through conducting interviews and a survey. The main aim of the interviews (conducted with industry and R&D experts) was to establish a vision element for each of the titanium metal value chain stages which was validated though the survey. Secondary data was then combined with the collected expert driven data in order to follow the selected roadmapping approach and complete a roadmap for each of the value chain stages following the specified layers (top-down approach). The vision elements were then combined to obtain an overall South African titanium metal value chain vision. The consolidated vision, based on what should be included in the South African titanium metal value chain and what not, was used as driver for compiling the overall South African titanium metal industry roadmap. This was done by considering and combining the required actions needed from the value chain stage roadmaps (top-down visioning approach) to achieve the identified overall roadmap (bottom-up visioning approach). The newly developed vision for the South African titanium metal industry is:

South Africa should continue to mine and upgrade titanium mineral concentrates in a sustainable and efficient manner. The country should commit to the establishment of two additional stages within the titanium metal value chain, which is $TiCl_4$ *production and titanium metal powder production. Capacity and expertise within the two already developed downstream stages (mill product and powder product production) should be expanded for both the local and the export markets. Within the mill product market, the focus should be on producing products for the medical, chemical and aerospace industries while the powder product markets should focus on medical, aerospace, leisure and automotive industries.*

In addition to the vision and roadmap establishment, other outcomes of this study indicated that the South African titanium metal industry is fragmented and should remain fragmented over the next decade. This thesis presents novel research on the production of a roadmap for a fragmented industry. To the best knowledge of the author, no other industry roadmap approach has first considered the production of individual roadmaps in a fragmented value chain and then combine them into a single overall industry technology roadmap. South Africa can apply the newly obtained titanium industry vision and roadmap, since there was no prior vision that addressed the development of the industry's fragmented value chain. The newly produced roadmap can be used to advance and develop the South African titanium metal industry in order to improve local value addition to the already existing resources.

Keywords: titanium, fragmented, titanium metal, value chain, titanium industry technology roadmap

Acknowledgements

This PhD dissertation was compiled under guidance and funding of the Advanced Materials Initiative (AMI) and within this initiative by TiCoC (Titanium Centre of Competence). I would thereby like to thank the CSIR for hosting me during the research period and giving me the bursary to conduct the study.

From the University of Pretoria I would like to thank my two study leaders: Prof Elma van der Lingen and Dr Anthon Botha for their continued support and guidance during my research. Prof Elma your guidance within the field of technology management and metallurgy was exceptional and your knowledge and experience admired. Dr Botha for your willingness to share your roadmapping experience with me and guiding me to produce a document that not only make sense to me, but hopefully anybody who dares to read it. I am honoured and privileged to have had the opportunity to learn from both of you.

From the CSIR I would like to thank my three supervisors: Dr Shaan Oosthuizen, Dr Annelize Botes and Dr Miemie Maminza. Each of you supervised me during different stages of my research and provided me with the much-needed resources and guidance. Thank you for all the coffees, conversations and discussions.

For Kobus & Lira

Table of Contents

List of Figures

List of Tables

List of Acronyms & Abbreviations

3D	Three-dimensional
AHRLAC	Advanced High-Performance Reconnaissance Light Aircraft
AC	Alternating Current
Al	Aluminium
AM	Additive Manufacturing
AMTS	Advanced Manufacturing Technology Strategy for South Africa
AMV	African Mining Vision
ASTM	American Society for Testing and Materials
BE	Blended Elemental
CAD	Computer-Aided Design
CHIP	Combined Cold and Hot Isostatic Pressing
CHM	Controlled Hearth Melting
CHM	Cold Hearth Melting
CIP	Cold Isostatic Pressing
CO_2	Carbon Dioxide
CP	Commercially Pure
CRPM	Centre for Rapid Prototyping and Manufacturing
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSIR-Ti	Council for Science and Industrial Research-Titanium (process)
CUT	Central University of Technology
DC	Direct current
DMR	Department of Mineral Resources
DOE	Department of Energy
DPR	Direct Powder Rolling
DSI	Department of Science and Innovation
dti	Department of Trade and Industry
dtic	Department of Trade and Industry and Competition
EBCHR	Electron Beam Cold Hearth Melting
EBM	Electron Beam Melting
EDM	Electrical Discharge Machining
EIA	Environmental Impact Assessment
EIRMA	European Industrial Research Management Association
ELI	Extra Low Interstitials
ESR	Electro-Slag Re-melting
FAPA	Ferro Alloys Producers Association of South Africa
FAST	Field Assisted Sintering Technology
FFC	Fray Farthing Chen
FTA	Future-oriented Technology Analysis
g	gram
g/cm^2	gram per square centimetre
g/mole	gram per mole
GDP	Gross Domestic Product
HCD	Human Capital Development
HDH	Hydride-dehydride
HIP	Hot Isostatic Pressed

IATA	International Air Transport Association
ICMM	International Council of Mining & Metals
IMTR	Integrated Manufacturing Technology Roadmapping
IPAP	Industrial Policy Action Plan
IRP	Integrated Resource Plan
ISM	Induction Skull Melting
kg	Kilogram
KMML	Kerala Minerals and Metals Limited
ktpa	Kilo ton per annum
kWh/m^2	Kilowatt hours per square meter
KZN	KwaZulu-Natal
LMD	Laser Metal Deposition
MER	Materials & Electrochemical Research
MIM	Metal Injection Moulding
mm	Millimetre
MNE	Multinational Enterprise
MPIF	Metal Powder Industries Federation
N	Nitrogen
NASA	National Aeronautics and Space Administration
NECSA	The South African Nuclear Energy Corporation
NGST	Next Generation Space Telescope
NLC	National Laser Centre
NNS	Near-Net Shape
O	Oxygen
OEMs	Original Equipment Manufacturers
P&S	Powder Pressing and Sintering
PA	Pre-Alloyed
PAM	Plasma-Arc Melting
PFD	Pore-Free Density
PGMs	Platinum Group Metals
PhD	Doctor of Philosophy
PM	Powder Metallurgy
PREP	Plasma-Rotating Electrode Process
PSD	Particle Size Distribution
PTA	Purified Terephthalic Acid
RBM	Richard's Bay Minerals
R&D	Research and Development
R	Rand
RAPDASA	Rapid Product Development Association of South Africa
SAAIR	South African Aluminium Industry Roadmap
SARS	South African Revenue Service
SDG's	Sustainable Development Goal's
SMME	Small-, Medium- and Micro-Enterprises
SONA	State of The Nation Address
SRG	Sector Roadmap Guidelines
STEMI	Science, Technology, Engineering, Mathematics and Innovation
Ti	Titanium
$TiCl_4$	Titanium Tetra-Chloride

TiCoC	Titanium Centre of Competence
TiO_2	Titanium Dioxide
tpa	Tonne per annum
TRL	Technology Readiness Levels
TWGs	Technology Working Groups
UK	United Kingdom
US	United States
US$	United States Dollar
USA	United States of America
USGS	United States Geological Survey
V	Vanadium
VAR	Vacuum Arc Remelting
$VOCl_3$	Vanadium Oxy-Trichloride
VPS	Vacuum Plasma Spraying
WBCSD	World Business Council for Sustainable Development
Zr	Zirconium
µm	Micron

1. Chapter 1 – Introduction and Background to the Research

1.1. Introductory Overview of the Study

Titanium metal is loosely referred to as the wonder metal. This metal exhibits numerous unique properties than make it ideal for selective applications within niche high value markets. Just more than a decade ago the South African government identified the titanium metal industry as one of the promising industries that should be re-elevated and developed (Van Tonder, 2010). Titanium is the ninth most abundant element in the earth's crust and South Africa has the world's fourth largest titanium mineral reserves. In 2017, South Africa was the largest producer of mined titanium (rutile combined with ilmenite) (USGS, 2018).

Based on these statistics one would assume that the country has a thriving titanium industry, but the technological gap for further processing (post mining) for high value downstream products is large. South Africa does not have a complete titanium metal value chain. In general, a complete titanium metal value chain starts at a titanium mine and ends with the finished titanium product with several steps in between. South Africa only mines titanium and then exports rutile or titanium slag (made from ilmenite) just to import the final titanium product. When a value chain for an industry displays these gaps, it is referred to as being fragmented. This fragmentation is a common observation across the global titanium value chain (Cardarelli, 2013; ILUKA, 2019).

Cardarelli (2013) discussed the fragmentation within the titanium industry value chain and noted that the titanium industry consists of companies that are located far from the consumption market. Titanium metal is critical for the use in a wide variety of applications, but in general the titanium metal industry is small (compared to the titanium pigment industry) with no single company influencing the industry's direction (BusinessDictionary, 2018; Cardarelli, 2013). Titanium companies are located across the globe and are involved in different stages of the titanium's value chain, creating a fragmented value chain referred to as production fragmentation. Production fragmentation is the geographical separation of activities involved in producing either goods and/or services across two or more countries (Athukorala and Yamashita, 2007).

Although South Africa has a significant amount of titanium minerals, the country's titanium industry is underdeveloped. After mining of the titanium minerals, South Africa exports ilmenite slag (upgraded ilmenite), mainly to China, to be used for titanium pigment production (Roskill reports, 2013). Minor quantities of rutile is exported to Japan and the USA to be used for titanium sponge production (Roskill reports, 2013).

The large quantity of local titanium reserves has motivated the South African government to investigate the expansion of the titanium industry (value addition) as one of the country's key action plans (IPAP, 2014; Du Preez, Damm and Van Vuuren, 2012; Roskill, 2019). The cost of a finished titanium part ranges from R 220 to R 260 000 (US$ 150 - 20 000). According to QuantecEasyData (2019) over the last decade South Africa imported an average of R 146 million worth of titanium products per year. The average export figure for the same time period is R 31 million per year.

In June 2011, the South African Department of Mineral Resources (DMR) published a report called "A Beneficiation strategy for the minerals industry of South Africa". The aim of this strategy was to provide "a strategic focus for South Africa's minerals industry in terms of developing mineral value chains and facilitating the expansion of beneficiation initiatives in the country, up to the last stages of the value chain" (DMR, 2011). Based on this, South Africa envisages to have the ability to process and utilise the titanium mineral concentrates locally.

The development of the titanium industry falls under one of South Africa's key action plans as set out in the Industrial Policy Action Plan (IPAP) report (IPAP, 2014). This report highlights the country's vision to improve and up-scale its industrial development objectives. The IPAP is addressed by a collaborative effort between the previous Department of Science and Technology (DST) and the previous Department of Trade and Industry (the dti) (IPAP, 2014). These two departments are now the Department of Science and Innovation (DSI) and the Department of Trade, Industry and Competition (the dtic). As one of the outcomes, the Council for Scientific and Industrial Research (CSIR), has been focusing on light metals development, especially titanium and aluminium (Govender, 2017). The CSIR's titanium research, has largely been funded by the DSI and through the formation of the Titanium Centre of Competence (TiCoC) (Govender, 2017).

The aim for government funded titanium research and development (R&D) in South Africa is to develop and create both a downstream and upstream industry for titanium. This aim originated from the African Mining Vision (AMV), which calls for beneficiation of local minerals. This vision aims to support industrialisation and economic growth (Bam and De Bruyne, 2017). For South Africa to enter the global titanium market an economical feasible approach that can compete with the existing markets is required. The CSIR has been focusing on a method that will be able to economically extract titanium metal from a titanium feedstock (Govender, 2017). This approach is called "the CSIR process" or "CSIR-Ti" and is based on extractive metallurgy to produce titanium metal powder. Other downstream processes for titanium part production have also been accelerated at the CSIR with one of the most significant processes the Aeroswift 3D project.

The local envisioned upstream processes for the titanium industry consist of South Africa mining and upgrading its own titanium resources, to produce the intermediate product, titanium tetra-chloride ($TiCl_4$). The extractive metallurgical approach is currently being investigated as a potential process to produce titanium metal powder directly without producing sponge. This process will eliminate the need for producing melted products (ingots, blooms, billets and slabs), as well as the further processing of these products to produce titanium metal powder.

The downstream applications of titanium metal powder represent a smaller market compared to the traditional mill product market. To date the powder market has been viewed separately from the mill product market. The main reason for this is cost. One of the aims of this study is to investigate the potential for producing mill products from cheap powder in South Africa. This could potentially lead to a market disruption.

Large technology gaps exist within the local titanium value chain. To be able to fill these technology gaps one must know what finished products are required. This has not yet been identified for South Africa, but as the country intends to enter the global titanium market, it has to focus on products that are internationally in demand. This study will therefore identify the potential titanium end products which could either be the high value traditional powder market (such as aerospace) or the lower value mill product market (such as sheets and pipes).

1.2. Problem Statement: South Africa’s Underdeveloped Titanium Industry

The South African titanium metal industry is underdeveloped with a highly fragmented value chain.

This problem statement calls for the local titanium metal value chain to be assessed and developed together with the identification of the industry gaps and goals. Globally the titanium value chain is also fragmented and only five countries have complete titanium metal value chains namely China, Russia, Kazakhstan, Ukraine and the USA. The fragmented nature of the titanium industry value chain in South Africa should be evaluated, and a better understanding obtained on whether this is a problem indeed, or a phenomenon that could fit in with the local circumstances. Although there seems to be a drive in South Africa to develop a complete titanium metal value chain the validity of this is unknown.

For South Africa to start benefiting from its abundant titanium mineral resources, a strategy needs to be identified and implemented to grow the titanium industry. The need for such a strategy has been identified in several reports (RAPDASA, 2016; DMR, 2011) and it was therefore proposed to compile a roadmap, designed to address the fragmentation within the titanium metal industry value chain and interpret the best possible route South Africa needs to take in order to be locally relevant and to enter the global titanium metal industry.

1.3. Research Objectives

The main objective of this research is to produce a roadmap for the titanium metal industry of South Africa. Three sub-objectives are:

- to establish the vision for the titanium metal industry of South Africa,
- to investigate the global titanium metal value chain, and
- to determine South Africa's position regarding the fragmented global titanium metal value chain.

From the objectives four keywords were selected (one from each) to be used in Chapter 4 to construct a conceptual framework for this study. These keywords are roadmapping, vision, value chain and fragmentation.

1.4. Research Questions

In order to address the research objectives, the following seven research questions were formulated.

1. Which roadmap type should be applied to the South African titanium metal industry?
2. What would the roadmap for the South African titanium metal industry look like?
3. What should the South African titanium metal industry vision be?
4. What does the global titanium metal value chain look like?
5. Which stage(s) of the titanium metal value chain is South Africa involved in?
6. Which stage(s) of the titanium metal value chain should South Africa focus on?
7. With regards to the fragmented titanium metal industry:
    a. Should South Africa be active in the complete titanium metal value chain?

    or

    b. Should the South African titanium industry value chain remain fragmented?

1.5. Relevance of the Research

Developing the titanium industry in South Africa will have large socio-economic benefits to industry, the government and the people of South Africa (Rokita, 2017). Currently South Africa is not fully utilising the economic benefits that its titanium resources offer as the country is exporting low cost titanium materials and importing high value fabricated titanium products.

This research aims to investigate the global fragmented nature of the titanium industry. Through understanding the fragmented nature of the industry, a clear vision for the South African titanium metal industry could be established. The main outcome of this research is the generation of a roadmap for the titanium metal industry of South Africa. It is the intention to establish whether roadmapping as a tool can be applied to study the nature and impact of fragmented industry value chains.

By applying this roadmap, the country could evolve beyond its current position in the global value chain. These improvements have the potential to not only better the local titanium industry, but to also grant South Africa an improved position within the global titanium metal industry.

1.6. Brief Overview of the Chapters

Chapter 1 is a brief introduction to the South African titanium industry. The chapter provides the problem statement and presents the research objectives as well as the research questions to be asked and the answers to be used to address the objectives. This chapter also introduces the reader to the relevance of the research.

Chapter 2 is a literature review on the two focus areas of this research, namely roadmaps and value chain fragmentation. Different types of roadmaps are discussed and the most common roadmapping structures are introduced. In this chapter, six working industry technology roadmaps were investigated to obtain a better understanding of the roadmapping principles (key aspects) in real life application. This chapter also introduces the reader to the global titanium metal value chain and discusses the fragmentation that affects this industry.

Chapter 3 is the conceptual research model. This mind model aims to provide guidance to the researcher in order to address all of the research questions. The conceptual model was composed using four main keywords namely the roadmapping, fragmentation, value chain and vision (of the titanium metal industry). Each of these keywords contribute to a specific layer of the conceptual model and are individually discussed in this chapter.

Chapter 4 is the research methodology. This chapter explains the processes and steps required by the researcher to complete the study and thereby answer the research questions linked to the research objectives. The methodology followed in this research was driven by collecting both primary and secondary data and this chapter explains how the data and the data collection plan contribute to answering the research questions. Ethical considerations and limitations were also addressed in this chapter.

Chapters 5 to 11 contain the result sections. Each of these chapters are dedicated to a specific stage of the titanium metal value chain. Each chapter starts with a literature review to explain the stage of the value chain and discusses the local and global position of the stage. The chapter then evaluates each specific stage in relation to the proposed roadmap layout considering where the stage is now, where the stage wants to go (vision element for each stage) and how the stage will get there.

Chapter 12 represents the titanium scrap and ferrotitanium industry. The recycling of titanium scrap and the production of ferrotitanium was not considered or included in the roadmap development for this thesis. It was decided to still present a chapter on these topics as it might have future impacts that render it important enough to be included. Titanium scrap can be re-melted into melted products for a reduced cost compared to producing titanium metal from minerals. In the stainless steel industry ferrotitanium is applied to the melted metal as a cleansing agent as it reacts with sulphur, carbon, oxygen and nitrogen to form an insoluble compound that get sequestered in the slag. Chapter 12 describes the processing steps for titanium scrap as well as the production and usage of ferrotitanium. The chapter also elaborates on the local status of titanium scrap recycling and the need for ferrotitanium.

Chapter 13 contains the discussion of four identified phases of roadmapping. The first phase includes planning and preparation. The second phase is the visioning proses for the roadmapping process. The third phase is the roadmap development, and the fourth phase roadmap finalisation. In the fourth stage the final roadmap for the South African titanium metal industry is introduced.

Chapter 14 addresses the conclusions and recommendations. This chapter concludes this research by discussing the outcomes, answering the research questions, stating the contributions to the knowledge base as well as recommending future research.

2. Chapter 2 - Literature Survey

The focus of this study is the evaluation and advancement of the South African titanium metal industry. The tool selected to do this is the application of roadmapping to this industry to indicate where the gaps are and what the next steps should be to advance this industry. Chapter 2 contains the bulk of the literature on roadmapping, setting the scene on why this tool was selected and how it would be applied. Mention is also made to the titanium metal industry and its fragmented nature. Additional literature on the titanium metal industry is presented in Chapters 5 to 12.

2.1. Introduction to Roadmapping

For institutions and industries to remain relevant they must effectively identify, select, acquire, exploit, protect and develop their technologies (Phaal, Farrukh and Probert, 2001). The process of doing this is an integral part of technology management. One of the methods used to conduct technology management is Future-oriented Technology Analysis (FTA). This is a future projection of current knowledge that aims to assist with the making of difficult decisions around technology and the impact it has on economic development (Haddad and Maldonado, 2017).

Roadmapping is a type of FTA tool that links technological innovations, policy, as well as business and social drivers together (Haddad and Maldonado, 2017). The term “roadmapping” is a verb derived from the word roadmap literally meaning a map of a road (Kostoff and Schaller, 2001). In business, the term roadmap is used as a metaphor for “a plan or strategy intended to achieve a particular goal” (Euiyoung, 2016). Carvalho, Fleury and Lopes (2013) describe the word roadmap as a summary of science and technology plans in the form of maps. The word roadmapping was described by them as the process of developing this roadmap.

According to Martin and Daim (2012) technology roadmaps can be used as a decision making framework by integrating emerging technology intelligence with established decision making and product development methods. Daim, Oliver and Phaal (2018), elaborated on the different ways roadmapping can be used as a tool with the main aspects highlighted as technology assessment, technology forecasting and technology intelligence analysis.

Roadmapping and especially Technology Roadmapping has become a necessity for large, global organisations (Whalen, 2007). The initial idea of applying roadmapping (specifically Technology Roadmapping) was initiated in 1970 by a former chairman of Motorola, Robert Galvin (Kostoff and Schaller, 2001). To Galvin the aim was to support improved alignment between technology and product development (Phaal, 2015a). Since the use of roadmapping by Motorola, this tool (in all forms) has become common practice in many companies (Euiyoung, 2016). Since the start of roadmapping in the 1970s this process is still applied to complex innovation concepts, the most recent being Industry 4.0. Roadmapping is being used to identify key design principles and technology trends applied by companies as a stepping stone to successfully transition into Industry 4.0 (Ghobakhloo, 2018). Daim and Zahra (2019) elaborates on the application of Industry 4.0 value roadmaps for the automotive, healthcare and telecommunication industries. The main aim of applying value roadmaps to these industries is to fill the gaps in project planning and to support strategy development, innovation and operational processes.

2.1.1. Types of Roadmaps

The usefulness of roadmaps are widely accepted and roadmapping as a tool is used by governments, international organisations, industrial bodies, science councils and companies (Letaba, 2018). Roadmapping as a tool is becoming increasingly flexible resulting in the establishment of countless types of roadmaps for several purposes (Phaal, Farrukh and Probert, 2004). Various authors have attempted to classify roadmaps into different types. Within these classifications major overlap occurs. From the literature it was observed that most roadmap types can be incorporated into classifications done by Phaal, Farrukh and Probert (2001), Kostoff and Schaller (2001) and Haddad and Maldonado (2017).

Phaal, Farrukh and Probert (2001) stated that for an organisation to correctly conduct roadmapping, it needs to clearly specify what it aims to achieve through the roadmapping process. They elaborated on the different purposes of roadmapping and stated that the specific purpose of the roadmap will determine the focus. These focus points, with an example of each, are displayed in Table 1.

Table 1. Focus points for generic roadmap design with descriptions and examples (Source: Phaal, Farrukh and Probert, 2001) .

Focus Point	Description	Example
Product planning	This is by far the most common type of technology roadmap, relating to the insertion of technology into manufactured products, often including more than one generation of product.	A Philips roadmap, where the approach has been widely adopted. The example shows how roadmaps are used to link planned technology and product developments.
Capability Planning	This type or roadmap is like product planning, but is more suited to service-based enterprises, focusing on the insertion of technology into organisational capabilities.	A Post Office roadmap (T-Plan application), used to investigate the impact of technology developments on the business. This roadmap focuses on organisational capabilities as the bridge between technology and the business, rather than products.
Strategic Planning	This type of roadmap includes a strategic dimension, in terms of supporting the evaluation of different opportunities or threats, typically at the business level.	A roadmap format developed using T-Plan to support strategic business planning. The roadmap focuses on the development of a vision of the future business, in terms of markets, business, products, technologies, skills, culture, etc. Gaps are identified, by comparing the future vision with the current position, and strategic options explored to bridge the gaps.
Long Range Planning	This type of roadmap is used to extend the planning time horizon and is often performed at the sector or national level (i.e. foresight).	A roadmap developed within the US Integrated Manufacturing Technology Roadmapping (IMTR) Initiative (one of a series). This example focuses on information systems, showing how technology developments are likely to converge towards 'information driven seamless enterprise'.
Knowledge Asset Planning	This type of roadmap focuses on aligning knowledge assets and knowledge management initiatives with business objectives.	This form of roadmap has been developed by the Artificial Intelligence Applications Unit at the University of Edinburgh, enabling organisations to visualise critical knowledge assets, and the linkages to the skills, technologies and competences required to meet future market demands.
Programme Planning	This type of roadmap focuses on the implementation of strategy, and more directly relates to project planning (for example, R&D programmes).	A National Aeronautics and Space Administration (NASA) roadmap (one of many) for the Origins programme, used to explore how the universe and life within it has developed. This roadmap focuses on the management of the development programme for the Next Generation Space Telescope (NGST), showing the relationships between technology development and programme phases and milestones.
Process Planning	This type of roadmap supports the management of knowledge, focusing on a particular process area (for example, new product development).	A type of technology roadmap, developed using T-Plan to support product planning, focusing on the knowledge flows that are needed to facilitate effective new product development and introduction, incorporating both technical and commercial perspectives.
Integration Planning	This type of roadmap focuses on the integration and/or evolution of technology, in terms of how different technologies combine to form new technologies.	A NASA roadmap - (also Origins programme), relating to the management of the development programme for the NGST, focusing on 'technology flow', showing how technology feeds into test and demonstration systems, to support scientific missions.

Kostoff and Schaller (2001) elaborate on the types of roadmaps identified by researchers at a workshop held in 1998. The approach these researchers followed was to look at more than 250 roadmaps and state their field of relevance. The result of the workshop was grouping of seven major types of roadmaps. The seven types of roadmaps identified in 1998 are discussed in Table 2.

Table 2. Seven different types of roadmaps with short descriptions (Adapted from: Kostoff and Schaller, 2001; Amer, 2013; Euiyoung, 2016; Johnson, 2016; Letaba, 2018; Smartsheet, 2019).

Type of Roadmap	Description
Science/research roadmaps	These roadmaps aim to produce a presentable image that satisfy the decision makers with the view or vision of the future science and technology landscape available to them. These types of roadmaps set industry targets.
Cross-industry roadmaps	These roadmaps strive to improve product or company alignment for improved decision-making. This is done by combining several other roadmaps that address the same need, thereby enabling the sharing and consolidation of R&D, supply-line and other common resources.
Industry roadmaps	Industry roadmaps or industry technology roadmaps focus on forecasting the development, commercialisation, and deployment of a new technology. These types of roadmaps set the industry expectations.
Technology roadmaps	Technology roadmaps enable companies to evaluate future technological developments within an environment of constant change. These types of roadmaps elaborate on the plans, systems and processes required to deliver the product or service(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016)(Johnson, 2016).
Product roadmaps	The main aim of product roadmaps is to ensure that a company's product strategy is up to date. This is done by visualising upcoming market trends based on past, current and future product line-ups over time.
Product–technology roadmaps	Product-technology roadmaps are an interplay between the two respective roadmaps. These types of roadmaps are produced to align business decisions.
Project/issue roadmaps	These types of roadmaps are high-level, easy-to-understand representations on the important aspects of a project. Project/issue roadmaps are mainly used by project managers.

In 2001, three years after identifying the seven roadmapping types at the workshop, the roadmaps were further grouped into four categories. The seven initial and the four final classifications are displayed in Table 3.

Table 3. Roadmap classifications (Adapted from: Kostoff and Schaller, 2001).

Roadmap classifications				
1	Science/research roadmaps	→	1	Science and Technology
2	Cross-industry roadmaps		2	Industry technology
3	Industry roadmaps			
4	Technology roadmaps		3	Corporate or product-technology
5	Product roadmaps			
6	Product-technology roadmaps			
7	Project/issue roadmaps		4	Product/portfolio management

From all of the different types of roadmaps discussed in Table 2 and Table 3, the most used type is the technology roadmap. Technology roadmapping even has evolved into a research discipline of its own (Letaba, 2018). The broad goal of technology roadmaps are to act as a market planning tool that can be used to translate strategies into implementation actions with clear targets and timelines (Letaba, 2018). Letaba (2018) further elaborates on this by stating that a technology roadmap is a tool used to select candidate technologies that are in line with the specific organisation's business strategy. The roadmap should therefore anticipate emerging and future technology trends while ensuring that the applied technology could stimulate growth. Technology roadmaps are generally designed internally by engineering and operation teams (Johnson, 2016).

According to Euiyoung (2016) researchers define a technology roadmap as a strategic plan to develop the required technology or to obtain the required technology in order to sustainably produce their product (Euiyoung, 2016). Once the strategic plan is produced it can be presented as a strategic technology roadmap in a visual presentation combining different modes of knowledge with specific activity layers. Ahlqvist et al. (2013), elaborated on two technology roadmapping cultures used to produce strategic technology roadmaps. The first is the culture of technology. Here roadmapping is approached as a normative instrument used to identify relevant emerging technologies while aligning them with project plans as well as related action steps. The second culture is emerging in strategic roadmapping and is a more dynamic and iterative process that produces visualised long-term visions as well as short to medium terms strategies on how to reach the vision. Roadmapping in this strategic form follows an adaptive process-based methodology that is suited for a systemic context that considers both time as well as selected roadmapping layers (e.g. market, technology, R&D and resources) (Ahlqvist et al., 2013).

In contrast to the already discussed roadmap classifications Haddad and Maldonado (2017) classified roadmaps into only two types namely corporate and sector roadmaps stating that these are the two main traditions of roadmapping. Corporate roadmaps focus on corporate level and the aim is to explore and communicate the relationship between markets, products and technologies (Haddad and Maldonado, 2017). Haddad and Maldonado (2017) indicated that the corporate roadmap type is similar to the four classification types identified by Kostoff and Schaller (2011).

Haddad and Maldonado (2017) further discussed the sector roadmap as a roadmap with a sectoral and national level focus on macro-level dynamics and micro-level developments that highlights trends and policies. These types of roadmaps are displayed as multi-layered strategy maps (Haddad and Maldonado, 2017). Additional inputs on the generation of sector roadmaps from the World Business Council for Sustainable Development (WBCSP) and the Dutch Ministry of Economic Affairs will also be discussed in this section.

The basis behind the Haddad and Maldonado (2017) sectoral roadmap classification was that the roadmap needed to be policy driven. Haddad and Maldonado (2017) stated that a sector roadmap is highly dependent on policy makers to consider the technological and social environments and to create policies accordingly. The required policies will be guided by functions identified to help the sector get from where it is, to its future state (where it wants to be). Each of these functions should be discussed as a one dimension of analysis for the roadmap (i.e. the drivers). The functions should act as a map for the policy makers to get from the current state of the sector to the desired future state of the sector (Haddad and Maldonado, 2017). If the functions are applied in accordance to the policies the design could be beneficial to technology and social environmental development when the design is future-oriented in the following ways (Haddad and Maldonado, 2017):

- building a common vision,
- facilitating systemic change by identifying social needs that require new solutions,
- anticipating the emergence of a new market,
- understanding the interdependence of the different layers of the roadmap, and
- identifying specific innovation targets.

In addition to the description given by Haddad and Maldonado (2017) on sector level roadmapping, the lessons and good practices identified through a study sponsored by the Dutch Ministry of Economic Affairs should be considered. In this study 78 roadmapping initiatives were reviewed to determine how roadmapping can support national innovation policy and systems (De Laat, 2004). A summary of these “good practices and lessons” was produced by Phaal (2020b) and is displayed in Table 4.

Table 4. Good practices and lessons learned from investigating 78 sector level roadmaps (Source: Phaal, 2020b).

Planning	• The roadmapping initiative should be clearly linked to broader strategy initiatives (for example, national innovation priorities). • It is much easier to launch a roadmapping activity within an existing 'social infrastructure' (for example, an industry association). • In order to mobilise participants there must be a sense of 'urgency'. • Creating high-level commitment from the start is critical, involving decision makers within companies (and government) throughout the process. • Visioning and goal setting are important, as a focus for developing consensus within the community. • Industry oriented roadmapping activities should be owned by industry from the outset to encourage take-up. • A clear link to decision-makers is important if roadmapping is to have impact.
Implementation	• No single format is suitable for all situations – the approach generally has to be customised. • It is important that momentum is sustained, to keep participants interested and involved. • Roadmapping is inherently exploratory in nature, and so the plan should be flexible to accommodate learning as the process advances. • A spirit of openness is important, to encourage new participants and thinking throughout the process. • The financial aspects need to be clear – generally the costs of such initiatives are shared between the administrating and participating organisations.
Follow-up	• Roadmapping is typically an iterative process, benefiting from review after the first roadmap is produced. • Outcomes should be monitored, including uptake and impact.

The good practices and lessons learned displayed in Table 4 can be applied in three stages to sector level technology roadmapping. The planning, implementation and follow-up stages displayed in Table 4 should be used throughout the preparation and focussing process especially for existing science and technology policy instruments such as national research programmes (De Laat, 2004). Sector level roadmapping conducted on a given research or technology area can boost the effectiveness of the roadmapping exercise by applying the three stages presented in Table 4 (planning, implementation and follow-up).

In 2018, the WBCSP published the Sector Roadmap Guidelines (SRG). According to this report, a sector roadmap enables companies to collaborate and articulate a common approach of how the involved industry can maximise its potential to contribute to achieving a common goal. The Sustainable Development Goal (SDG) Sector Roadmap indicates that the ideal is for the sector to have one big roadmap (that guides relevant companies to the common goal) and then for individual companies within the sector to have separate roadmaps with a personal approach to reach the common goal. Key steps for a generic roadmapping framework as recommended by WBCSD (2018), is displayed in Table 5.

Table 5. Key steps involved in a generic sector roadmap (Adapted from: WBCSD, 2018).

	Establish current position	Identify key impact opportunities	Call to action
Objective	• Understand the sector's level of impact for entity measured across the value chain	• Conceptualise where the sector can make the largest contribution to the measured entity collectively	• Inspire the sector and others to take action to reach the goals
Main Activities	• Map measured entity level of impact across the sector value chain • Prioritise entity measured for the sector	• Identify key impact opportunities to drive progress towards realisation of the measured entity • Assess sector apportionment	Identify barriers, potential solutions and impact accelerators for the sector Identify short-, medium-, and long-term actions to advance measured entity opportunities Monitor, measure and report progress
Outcome	• Priority entities for the sector to address	• Key impact opportunities for the sector	• Action plan for the sector

Although there are several types of roadmaps available, a generic roadmap model has been created by the European Industrial Research Management Association (EIRMA) in 1997 for technology roadmapping (EIRMA, 1997). This model was devised based on the fact that the most common feature of roadmaps is the use of a graphical or tabular format to display a high level, synthesised and integrated view of strategic planning (Phaal, Farrukh and Probert, 2005). This generalised roadmap design can be used as the basis of all roadmaps with adaptations and changes that can be applied to produce the required type of roadmap.

2.1.2. Generic Roadmapping Design for Technology Roadmaps

The link between the different types of roadmaps is vague and overlaps are common. The first attempt to simplify roadmapping was presented by EIRMA in 1997. The simplification was captured in a graphical representation of roadmapping (Figure 1). EIRMA (1997) produced a generic roadmapping form that incorporated a time-based chart that consisted of several layers. The main focus of the chart was to enable the evolution of markets, products and technologies and therefore enabled the commercial and technological perspectives of roadmap development (Phaal, Farrukh and Probert, 2001). The generic technology roadmap structure of EIRMA (1997) is presented in Figure 1.

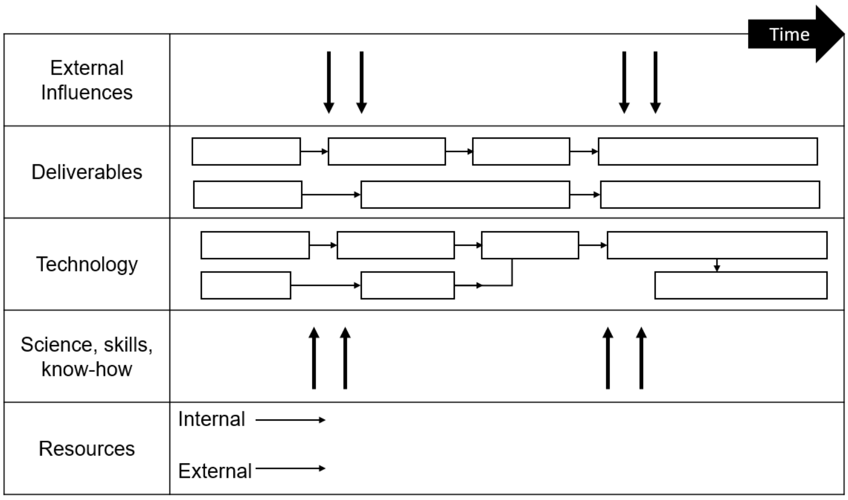


Figure 1. The generic technology roadmap by EIRMA (1997).

Since the development of the generic technology roadmap format in 1997, several improvements and adaptations have been made to this layout. Countries that contributed the most to roadmap development were the United States (Portland State University) and the United Kingdom (University of Cambridge) (Letaba, 2018). Figure 2 is an example of a modified version of the generalised technology layout. This multi-layered time-based chart indicates how various functional strategies align (Phaal, Farrukh and Probert, 2005). The connection between the different types of roadmaps are that they all strive to answer three questions in respect to the markets, the products and the technology. These three questions have been indicated on the bottom of Figure 2.

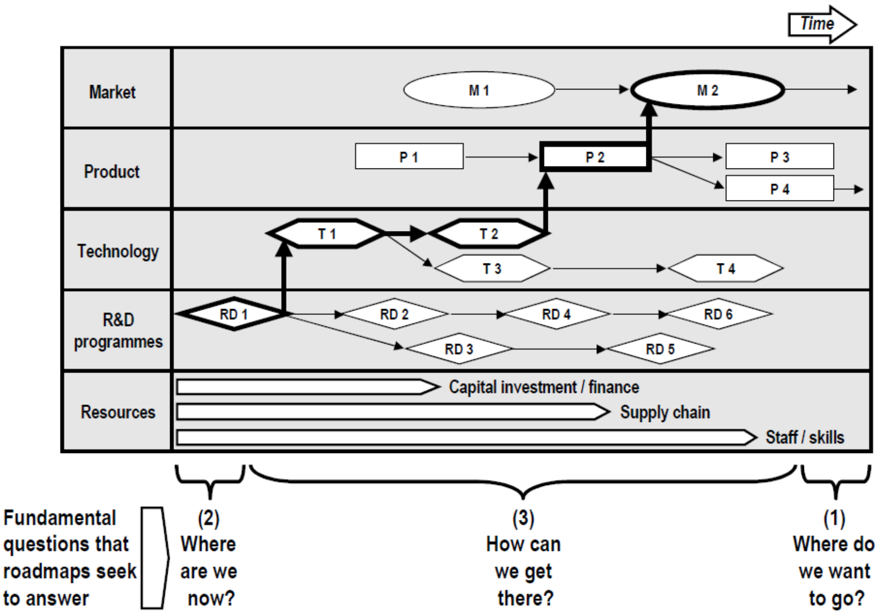


Figure 2. The generalised multi-layered layout for roadmapping (Source: Phaal, Farrukh and Probert, 2005).

Three additional questions can also be placed on the y-axis namely “Why do we need to act?”, “What should we do?” and “How can we do it?”. The “why” requires the roadmaping to identify what the business and market environment conditions are that influence the company’s behaviour (Phaal, 2015b). The “why” determines the reasons (purpose) why the company is doing what it is doing. The “what” requires a visualisation of the product/service under development, as well as the capabilities of the development (Phaal, 2015b). The “what” elaborates on the mechanisms (know-how) of how the purpose is achieved (Phaal, Farrukh and Probert, 2005). The “how” requires the roadmap constructor to identify the necessary resources for achieving the firm’s goal (Phaal, 2015b). The resources can include technology, R&D programmes, as well as any additional resources needed.

To better understand the construction of a generalised roadmap, a range of layers and sub-layers are needed within this layout. These layers are illustrated in Figure 1 and Figure 2. An important component on most of the roadmapping layouts is “time” represented by the x-axis. Time brings a “when” component into roadmapping (Phaal, Farrukh and Probert, 2005; Phaal, 2015b).

Roadmaps can also vary in complexity displayed on the graphic. Both Figure 1 and Figure 2 are simplified roadmaps. These roadmaps have a simple structure that contains significant information, while complex structured roadmaps often have sparsely populated information. Phaal (2020a) grouped the complexity of roadmaps into three types based on the most common roadmaps used. This classification is displayed in Figure 3.

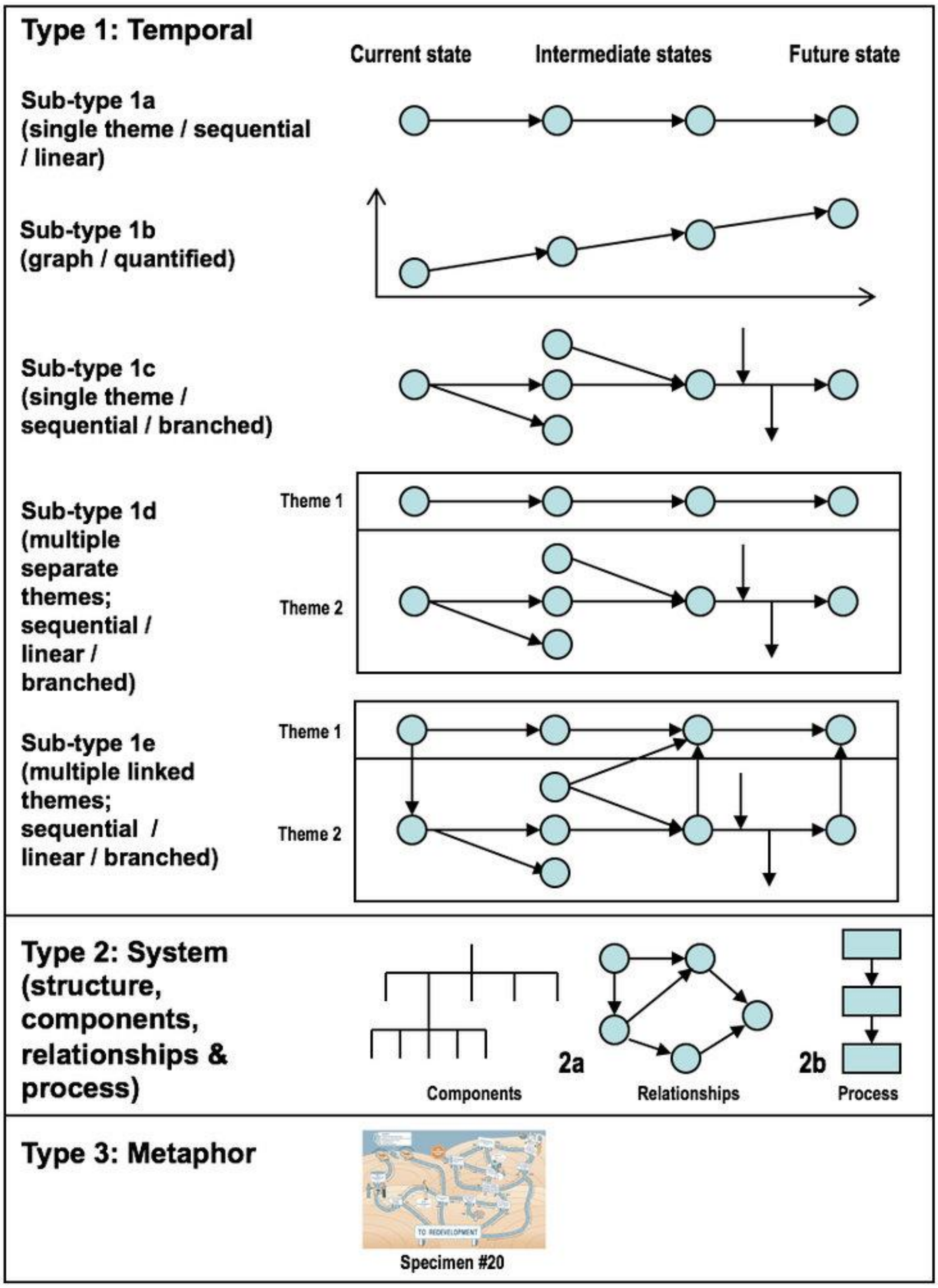


Figure 3. Roadmap complexity classification (Phaal, 2020a).

Figure 3 indicates three types of roadmaps. The first type is temporal roadmaps and comprises of one or more time-based layers. This is the most common roadmapping type and has several sub-types also with different complexities. The second type is referred to as system roadmaps, and use structures, components, relationships and processes. According to Phaal (2020a) these roadmaps do not include the time dimension and are actually building blocks of roadmaps. The third type of roadmap displayed in Figure 3 is a metaphoric roadmap that uses a pictorial approach. This could be in the form of roads, mountains, board games or similar visual displays (Phaal, 2020a).

The visualisation of roadmaps can be a strong enabler of communication to the target audience. According to Kerr and Phaal (2015) this section of the roadmapping exercise has been neglected in literature as well as by roadmap developers and this has resulted in roadmaps not achieving their full potential as a communication tool. In the article Kerr and Phaal (2015) elaborate on presenting a roadmap in a way that the key information is alighned to the requirements of the audience and that the visual representation of the roadmap is clear and meaningful to the target audience.

When constructing a roadmap in general, two main approaches can be followed to collect input. The first is expert-based and the second is computer-based. A third approach to consider is the hybrid approach, which is a combination of the first two.

An expert-based approach is highly dependent on the knowledge and experience of humans. This means that if this approach is followed, a team or teams must conduct the roadmapping. The team should be comprised of different technology working groups (TWGs) each group being an expert in their field (Kostoff and Schaller, 2001). Depending on the size of the project, a TWG can be composed of a group of experts or an individual. At the start of a roadmapping exercise, it is often impossible to say what the end product will look like. This creates a challenge in that neglecting to obtain the correct expert input could lead to gaps in knowledge that only is noticed at a mature stage of roadmapping. This can be overcome by making the roadmapping process interactive (Kostoff and Schaller, 2001).

The computer-based approach is dependent on large computer-based databases that could include published papers, reports, memoranda and letters. These databases must already exist and could have been generated from any relevant field such as engineering, science, statistics or technology (Kostoff and Schaller, 2001). A summary of the differences between the expert-based and computer-based approaches are displayed in Table 6.

Table 6. Differences between the expert-based and computer-based roadmapping approaches (Adapted from: Kostoff and Schaller, 2001).

Expert-based approach	Computer-based approach
Less objectivity	More objectivity
Exposed to preconceived limitations, constraints, biases and personal and organisational agendas of the experts	No preconceived limitations, constraints, biases and personal and organisational agendas of the experts
Confined to time (retrospective approach, a technology-push prospective approach and a requirements-pull prospective approach)	Does not start from one point in time, but generates a network of points by looking at the available data
Expert interaction	Lack of interaction with experts

The hybrid approach to roadmapping combines the expert-based approach with the computer-based approach with the aim to generate the best possible outcome (Kostoff and Schaller, 2001). This combination is the popular choice and will also be used in this study – computer based since market studies such as Roskill (Roskill, 2019; Roskill, 2013) that depends on large databases and also literature databases were used for peer reviewed articles; and expert base, since the opinion of domain experts were solicited for constructing the roadmap.

2.1.3. Roadmapping Analysis

After deciding which approach should be taken to collect input for the required roadmap one can decide on which analyses approach will be the best. Kostoff and Schaller (2001) describe two clear forms of analysis namely a retrospective and a prospective analysis approach. Kostoff and Schaller (2001) further indicate that both can be sub-divided into technology-push and market-pull approaches. A simple illustration of the prospective and retrospective approaches is presented in Figure 4.

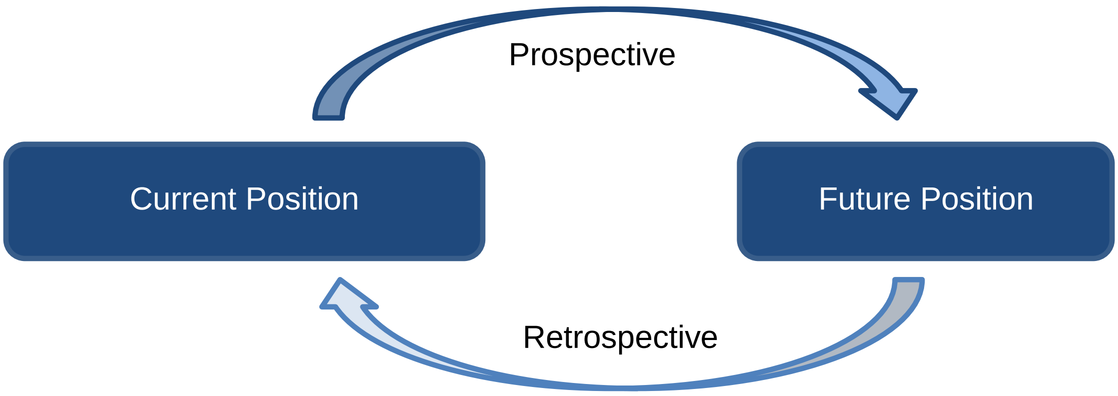


Figure 4. A basic illustration of a prospective and retrospective analysis approach.

When taking a retrospective approach, one will start with the successful final product and work backwards to identify the factors that made it successful (Kostoff and Schaller, 2001). When a retrospective analysis is followed the roadmap would cover time frames from decades back up to the current situation. When taking a prospective roadmap approach, one looks forward from the current position and considers what is required for future directions. This roadmap would therefore consist of time frames of the current into the future (Kostoff and Schaller, 2001; Whitelock and Brasher, 2006).

Both prospective and retrospective approaches can then be subdivided into a technology-push, a market-pull or a combination of the two. A technology-push approach focuses on developing a new technology that would drive the development of new products. This roadmapping approach would start with the existing research project and complete the roadmap by identifying the diverse possibilities that the research could lead to and developing the technologies to get there (Whitelock and Brasher, 2006). For this approach it is key “to stick to the plan” (Kostoff and Schaller, 2001). When considering a market-pull roadmap one must start with the desired end state and identify the R&D that will be required to arrive there. The market-pull approach refers to the need for a solution to an existing problem as seen from a market perspective (such as competitiveness). This approach is requirement driven as it needs to solve the original need (Kostoff and Schaller, 2001; Whitelock and Brasher, 2006).

A technology–push/market-pull as a combination roadmap is also a possibility. An example of this is a roadmap will start with an existing science or technology development program. This could be either technology or market driven. The roadmap then needs to identify the research gaps which prevent advances and diversity of end products to which successful development could lead (Kostoff and Schaller, 2001).

2.1.4. The Roadmapping Vision

Roadmaps, and more specifically technology roadmaps provide a consensus view of the future landscape available to decision makers (Kostoff and Schaller, 2001; Londo *et al.*, 2013). This future view is referred to as the roadmapping vision which is the desired state of any business planning and technological development (Phaal, Farrukh and Probert, 2004). A vision is essential for good roadmapping as it represents the common focus (Botha *et al.*, 2017). It is important to note that a vision usually only focuses on outlining the desired future (such as a specific technology) and not the path towards it (Londo *et al*., 2013). This path still needs to be established and therefore the establishment of a vision can serve as a starting point of a technology roadmap (Londo *et al.*, 2013). The vision of a roadmap is graphically displayed in Figure 5.

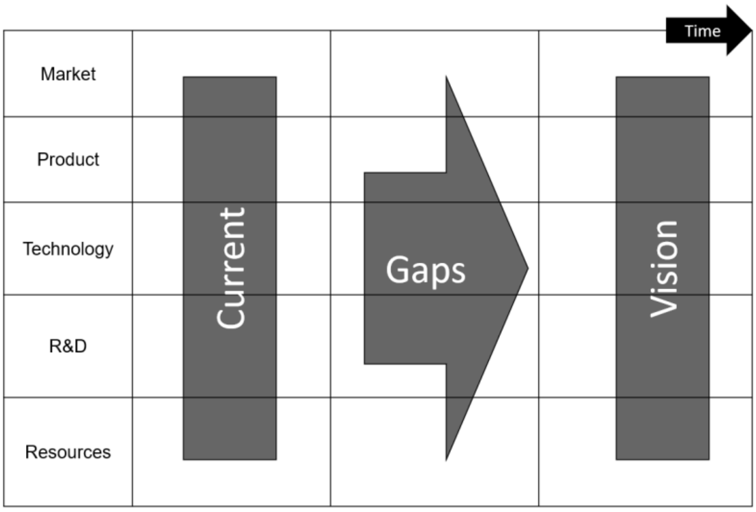


Figure 5. The vision of a roadmap (Adapted from: Phaal, 2016).

A vision is required to set the path for future action in an industry. Once this vision has been established it will guide the thinking along the levels of a roadmap which are market, product, technology, knowledge (often from R&D as shown in Figure 5) and resources (Botha *et al*., 2017). One of most important outcomes of establishing the vision of a roadmap is the identification of gaps. Gaps are identified when the future vision is compared with the current position (Phaal, 2016). Once the gaps have been identified strategic options can be explored to bridge the gaps (Phaal, 2016).

The vision establishment of a technology roadmap is as flexible as the whole roadmapping process. Londo *et al.* (2013) indicate that the roadmap and the roadmapping process can be adapted to suit a particular context. From the analysis conducted by Londo *et al.* (2013) it was observed that only a few elements within roadmapping were consistent. From their research it was noted that a clear roadmap vision/target was not the norm as a clear vision/target was missing from almost half of the technology roadmaps reviewed. This finding by Londo *et al.* (2013) correlates with results obtained from the current study in relation to technology roadmaps that will be analysed in Section 2.1.6. The methodology used to establish a technology roadmap vision is therefore not set in stone.

Although there is not a set methodology for setting up the vision for a technology roadmap standard there is an industry standard. The bulk of the literature that elaborates on the visioning process states that the vision was established through input from industry experts (Londo *et al*., 2013; SAAIR, 2017; MPIF, 2012). This input could be obtained from visioning workshops, conducting interviews or through surveys.

Although the roadmap vision is essential for most roadmapping processes, it also comes with limitations. Londo *et al.* (2013) state that selecting a vision has the potential to focus the roadmap on a single collective future vision. This could lead to a reduced attention for uncertainties, variety and diversity that are seen as healthy aspects in many strategic initiatives. Londo *et al.* (2013) also state that this risk can be minimised by applying key success factors to a roadmapping process such as initiation, implementation and follow-up. Initiation refers to establishing a clear vision with sufficient support from the decision makers. Implementation refers to the ability to retain flexibility during the roadmapping process. Follow-up refers to the ability to continuously update the roadmap while monitoring the outcomes and impacts.

2.1.5. Industry Technology Roadmaps

Considering the South African position within the global titanium industry, it was decided to create a roadmap format specific to the South African titanium industry. The roadmap type selected was the industry technology roadmap. The main reason for selecting an industry technology roadmap as the type of roadmap for this research is that its focus is on foresighting the development, commercialisation and deployment of a new technology (Amer, 2013).

Literature on industry technology roadmaps is limited (Botha *et al.,* 2017). These types of roadmaps are generally designed for a specific industry and/or country. The roadmapping approach presented by industry technology roadmaps could be retrospective or prospective and the style and content does not follow a set layout (Botha *et al*., 2017). From an academic point of view little to no consistent methodological approaches were found across the development of technology roadmaps. Literature indicated gaps regarding the relationship between the applications of technology roadmaps and positive innovation performance outcomes. Examples of these outcomes are an increased number of patents being produced, a reduction in the time needed for product development and an increase in the sale of newly developed products (Carvalho, Fleury and Lopes, 2013).

In an article published by Botha *et al.* (2017) the development of an conjunctural industry roadmap for the South African aluminium industry was discussed. According to the authors a conjuncture is a *"period during which the different social, political, economic and ideological contradictions that are at work in society come together to give it a specific and distinctive shape".* This approach was followed by Botha *et al.* (2017) to consider the complexity of South Africa's dynamic socio-economic, political, environmental, labour, cultural and technological needs. In the South African aluminium industry roadmap, the conjunctural approach was especially helpful during the visioning process as it helped to direct the confluence of social, political and economic forces that had a direct impact on the developing roadmap. The roadmap to be produced for this thesis will have an academic theme. Industry opinions will be obtained to produce the roadmap but not direct industry buy in was considers which is needed for a conjunctural industry roadmap.

Applying industry technology roadmapping, as a tool can lead to the effective analyses of the future market direction(s), the identification of the path for the key technology(ies) and could be used to plan research and development projects (Li *et al.*, 2013). With the correct application of this type of roadmap three problems should be solved namely (Li *et al*., 2013):

- the supply capacity of the scientific and technological resources,
- the ability to grasp the market demand, and
- the construction of effective institutional mechanisms between supply and demand (the product).

This type of roadmap also considers the effective and rational allocation of resources to enable innovation and competitiveness within the selected industry (Li *et al.,* 2013). Tong and Li (2011) described industry technology roadmapping as an open, complex giant system where the roadmapping takes place as a form of complex system modelling.

Although the industry roadmap description as laid out by Amer (2013) is suitable to the development of a roadmap for the titanium metal industry, it should be noted that the titanium industry has a fragmented value chain and no roadmap to date (to the author's knowledge) has taken this fragmented nature into consideration. The generic outline of a technology roadmap will therefore act as a guide and if needed changes to this basic outline will be applied to compensate for the industry's fragmented nature. Changes that will be applied to the generic technology roadmap will form part of one of the objectives of this research which is to produce a roadmap specific to the South African titanium metal industry.

2.1.6. Relevant Industry Roadmaps

From the literature review, it has been observed that technology roadmapping, especially industry technology roadmapping, is often used to develop, commercialise and deploy new technologies. The application of industry technology roadmaps is applicable to any industry that wants to remain innovative and competitive. Keeping this in mind a search was conducted to find roadmaps for the titanium or related industries (such as other light metals). A total of 13 roadmaps were obtained for the light metals industry (including titanium) and are introduced in Table 7.

Table 7. Light metal roadmaps (titanium and aluminium).

Title	Sector	Source
A South African Additive Manufacturing Strategy	Powder Metallurgy (PM), Industry wide Additive Manufacturing	(RAPDASA, 2016)
Additive Manufacturing Technology Roadmap for Australia	Titanium Metal Powder, Additive Manufacturing	(Wohlers Associates, 2011)
Technology Update for the Powder Metallurgy Industry. PM Industry Roadmap	Powder Metallurgy (Industry wide)	(MPIF, 2012)
Vision 2020: Future Developments for the European PM Industry. The European PM Industry Roadmap	Powder Metallurgy (Industry wide)	(EPMA, 2004)
Measurement Science Roadmap for Metal-Based Additive Manufacturing	Powder Metallurgy, Industry wide Additive Manufacturing	(Energetics Incorporated, 2013)
Standardisation Roadmap for Additive Manufacturing	Powder Metallurgy, Industry-wide Additive Manufacturing	(AMSC, 2017)
The 2016 Thermal Spray Roadmap	Powder Metallurgy (Industry wide), Thermal Spray	(Vardelle *et al.*, 2016)
International Air Transport Association (IATA) Technology Roadmap	Aerospace	(DLR, 2013)
Manitoba Aerospace Technology Roadmap	Aerospace	(ASDL, 2015; Manitoba Aerospace, 2017)
IATA Technology Roadmap	Aerospace	(ASDL, 2015)
South African Aluminium Industry Roadmap	Light Metals, Aluminium	(SAAIR, 2017)
The Aluminium Industry Technology Roadmap (USA)	Light Metals, Aluminium	(The Aluminum Association, 2003)
Canadian Aluminium Transformation Technology Roadmap	Light Metals, Aluminium	(RéseauTrans-Al, 2006)

The roadmaps listed in Table 7 are examples of roadmap reports generated by industry for industry use. It was decided to analyse the layout and content of six of the roadmaps listed in Table 7. The aim of analysing these roadmaps were to understand how the roadmaps produced for the titanium or related industries were constructed. The six selected roadmaps are those most relevant to the South African titanium industry as they are either applicable to South Africa or make mention of titanium.

To the author's knowledge no roadmap has been compiled for the titanium industry as a whole, although roadmaps have been generated for fractions within this industry (such as on additive manufacturing, see Table 7). Aluminium, on the other hand, is also a light metal and used in similar industries than titanium. Several aluminium industry roadmaps were obtained and due to the similarities between the two metals, aluminium roadmaps were included in this literature review for a titanium industry with a fragmented value chain. Roadmaps that mention titanium and roadmaps for South Africa were prioritised. Roadmaps on Additive Manufacturing (AM) and Powder Metallurgy (PM) as well as roadmaps for the aerospace industry made mention of titanium and were therefore included.

2.1.6.1. A South African Additive Manufacturing Strategy

In 2016, the Rapid Product Development Association of South Africa (RAPDASA, 2016) produced a roadmap for South Africa’s AM industry. This document was initially known as the South African Additive Manufacturing Technology Roadmap but was changed to the current title after consensus between the DSI and the team who developed the roadmap was reached. The reason for the name change was that the strategy that was developed as the outcome of the roadmap was believed to be an across-the-board strategy for the South African AM industry. By calling it a strategy the hope was that government line departments, as well as public and private sector stakeholders would more readily adopt the strategy as “a national strategy for Additive Manufacturing in South Africa”. This document frequently refers to titanium as an important part of the country’s AM industry, but the report was not limited to titanium.

The main aim of the South African Additive Manufacturing Strategy was to develop an implementation framework to guide public and private sector investment in AM research, development and innovation. Included in the implementation framework were action plans to take advantage of high-priority opportunities to contribute towards SA’s socio-economic imperatives. A secondary aim was to create a strategy to establish an AM grounded interest in science, technology, engineering, mathematics and innovation (STEMI) among industries, entrepreneurs and the public with the intention to educate and create awareness of AM among manufacturers, designers and entrepreneurs.

The South African Additive Manufacturing Strategy was divided into three main sections. The first section discussed the international landscape concerning the global trends and drivers within AM. The second section focused on the South African landscape and opportunities for AM and the related technologies. The third section provided and explained the strategy for South Africa’s AM industry. Four focus areas were identified in this section. It is important to note that there is not a single vision for this roadmap, but rather four visions for each of the identified focus areas. Each section will be explained in more detail.

The section on the international landscape explains how AM technology was initiated and why the growth has been so substantial lifting out the technology's advantages. The key industries adapting AM technology was identified as industrial/business machines, consumer products/electronics, motor vehicles, aerospace, medical/dental, academic institutions, government/military, architectural and others. The three future industries which are expected to provide the most promising business opportunities within the AM industries were identified as the aerospace, the automotive and the electronics industries (RAPDASA, 2016). This section also identified global markets and the current global leaders within AM.

The second section gave an insight on the South African landscape and opportunities within AM. Firstly, the local research trends and capabilities were discussed. AM was initially applied in South Africa in the early 1990s and since then technology growth was encouraged by associations such as the National Advanced Manufacturing Technology Strategy for South Africa (AMTS) followed by the RAPDASA. This section clearly indicated which institution (academic or science council) was focusing on which section of the required research and where commercial AM systems were already rolled out. This section also discussed the identification of local opportunities as guided by stakeholder workshops, international trends and by local capabilities. A short subsection was provided on local and global opportunities in each of the following sectors:

- aerospace and military,
- medical and dental,
- traditional manufacturing (the tooling industry, the casting industry and refurbishment),
- automotive industry,
- metals development,
- machine platform development (local development of low-cost three-dimensional (3D) printers and local development of high-end systems), and
- small-, medium- and micro-enterprise (SMME) sectors (jewellery, prosthetics, audiology and other application areas).

The third section focuses on South Africa and provides the strategy for South Africa's AM industry. This section starts out by discussing the priority focus areas and enablers. This means that the opportunities applicable to the country had to be identified and selected. The authors stated that the South African AM Strategy is focused on the development of niche areas that will enable access to high priority opportunities that can contribute towards South Africa's socio-economic imperatives. Drivers within the South African market should be applied to take advantage of South Africa's research and development capabilities, South Africa's natural resources and local markets and use these advantages to impact the country's economy.

In order to identify the strategy for the South African AM industry several country-specific opportunities were identified during a national workshop. These opportunities were then prioritised through an evaluation process that looked at attractiveness (need, value and potential) and fit (capability, national objective and likelihood or realisation) of each identified opportunity. The outcome was a classification of the identified opportunities into low, medium and high priority.

The next step was to create a strategy to guide the public and private sector investment in AM. The identified opportunities were used to create four specific focus areas, and these were listed together with the opportunities within each area. A breakdown of the focus areas was provided together with the vision, the drivers, the objectives and the possible outcomes of each.

The roadmap then proceeded to the identification of enabling capacities and the recommendation of further and continuous education, training and awareness. Enabling capabilities should be developed to ensure that the strategy is successfully implemented and included design optimisation, pre-processing, process monitoring and control, post-processing, testing and analysis, dimensional verification and reverse engineering as well as simulation and modelling. It was also stated that further education, training and awareness is needed to support the establishment of a sustainable AM industry in South Africa.

Similar to other roadmap implementation sections the South African Additive Manufacturing Strategy document also recommends the establishment of an AM Steering Committee to provide strategic leadership to ensure the correct implementation and support.

2.1.6.2. Additive Manufacturing Technology Roadmap for Australia

The Australian government recognised the economic impact additive manufacturing could have on the country and on the request of Commonwealth Scientific and Industrial Research Organisation (CSIRO) produced an Additive Manufacturing Technology Roadmap in 2011. The aim of this roadmap was to provide the Australian government and industry with direction and guidelines on AM and its possible acceptance on a national scale. Although this roadmap was constructed to include the AM of all metals, the main emphasis was on titanium.

This roadmap deviated from the generic roadmap methodology in that no workshop was held and no graphical representation of the roadmap was presented. Instead, the roadmap was presented in the form of chapters progressively building up to recommendations at the end. The roadmap was prepared by Wohlers Associates (2011) a contracted company to produce an industry-aligned AM technology roadmap. Wohlers Associates were given the following list of primary expected outcomes:

1. The roadmap should identify the markets, technologies and other drivers that are influencing the development of additive manufacturing technologies worldwide.
2. The roadmap should look at current, emerging and future market opportunities for additive manufacturing specifically for Australia.
3. The roadmap should identify any technologies and enablers that could be beneficial for the Australian additive manufacturing industry and take advantage of these opportunities.
4. The roadmap should include trends as well as a technology development path and forecast the opportunities in the targeted areas.
5. As the roadmap will be used as a guideline, it should provide a framework that will assist in planning, coordination and uptake of technology development by industry.
6. The roadmap should identify critical technologies, gaps and enablers.

Instead of arranging a workshop, Wohlers Associates compiled a draft report that was sent out to experts for comments. The draft was compiled using collective knowledge and experience of the authors. The end product (the roadmap) was an integration of the draft with inputs from more than 30 global experts in the titanium field.

The outlay of the roadmap started with a background on AM followed by the benefits of implementing the technology. The background discussed why AM is important and why Australia should develop the technology. The report also focused on the growth and potential of AM. The background of the local AM industry of Australia was discussed in context to what is currently happening globally. From this section of the report it was clear that the CSIRO has, prior to the development of the roadmap, identified the economic potential of the rapidly growing technology and stated that the global value of the AM industry is believed to be in the billions of dollars. Except for the high value end products that can be produced using this technology, the roadmap also emphasises that money is saved during manufacturing since less costly design errors occur and that less waste is generated (Wohlers Associates, 2011).

The AM technology roadmap of Australia discussed the strengths and limitations of AM technology. This includes the properties of the material and for example, compares metal parts made from additive manufacturing to plastic parts from the same process. Advantages and disadvantages are discussed highlighting the conditions that should be achieved for a sufficient product to be produced. This section of the report relied heavily on the feedback obtained from industry and the lessons learnt. When applying AM technology cost is an important consideration. The cost is determined resulting from the technology applied, the material selected to work with, the state of the material when exposed to AM and the properties required for the end product. Other limitations that were discussed, were additional finishing required for parts produced by PM, the need for anchors (prevent deformation) and the lack of industry standards for this growing technology. The next section of the report discusses the new opportunities brought forward by AM technology. This includes design freedom and the increased functionality. A single part produced through AM can replace a multicomponent part.

Wohlers Associates (2011) discussed the most suitable markets for AM. The main industries identified, by the Australian Additive Manufacturing roadmap, to benefit from the parts produced through additive manufacturing were aerospace and medicine. Other AM innovation markets open to AM identified included sport and recreation, jewellery and automotive.

The identified socio-economic aspects to be affected by the AM industry, were environmental savings, reduced CO_2 emissions, reduced water usage and less virgin material with less waste material generated. This results from parts produced by AM being more complex and could be made of one component compared to conventional part production where more than one-part components are required for the same function. The roadmap identified that new business opportunities will be established, new products will be produced, and new jobs will be created. The roadmap also indicates that by growing industrial research and education, innovation would excel.

Future opportunities and forecasts presented in the report indicated that the roadmap design was for medium and long-term. Medium-term extended to 2015 (four years) and the long-term roadmapping to 2025 (10 years from 2015). The future opportunities and market forecasts were discussed for the given terms.

The last section of the roadmap contained recommendations and the summary. The recommendations were designed to advise Australia on how to advance the development and adoption of the additive manufacturing technology. This closing section provides guidelines to assist with planning, coordination and the uptake by industry. Comparing this to the general roadmapping outline, this would form part of the implementation sector as reference is made to R&D facilities, centres of excellence that are needed and what should be done to ensure that the roadmap is implemented and the objectives reached.

2.1.6.3. PM Industry Roadmap (2012 - 2021) for North America

This roadmap was included in the study to highlight the importance of updating industry roadmaps. This updated version of the PM Industry vision and technology roadmap was released 10 years after the initial publication. The roadmap was produced by the Metal Powder Industries Federation in 2012 (MPIF, 2012). The aim of the first roadmap (published in 2001) was to sustain the growth rates of PM. The updated version of the roadmap was not produced to replace the initial roadmap, but the aim of the update is to incorporate new market drivers and highlight technical challenges that will further impact the industry's growth while redefining the technology. The vision for both the first and the second PM Industry roadmaps was for the PM industry to be/remain the preferred source of net-shaped and metal-based systems.

This roadmap discusses the general application of PM. The usefulness of titanium metal is mentioned for the aerospace and defence industries. Short mention was also made on the developing techniques to process and produce titanium powder and the challenges that accommodate the processes. This updated roadmap focused on the key markets, drivers, and technology development priorities. The document was structured accordingly.

Under the key markets and drivers, a short background was provided on the current state of the PM industry. The leading industry was identified as the automotive industry and growth is expected in several other industries such as medical, aerospace, energy, industrial and consumer products. The major drivers of each industry were discussed with emphasis on the environmental benefits the growth of PM will have.

When discussing the technology development priorities three focus areas were identified. These areas were high-density PM components, lightweight-materials processing and electrical and electromagnetic applications of PM. Each of these areas were then discussed individually focusing on the materials, the processes as well as the challenges.

The PM Industry Roadmap highlighted additional technology and manufacturing improvements and marketing initiatives that were important for the PM industries growth over the following 10 years. An appendix of the roadmap discussed past achievements related to the first roadmap. A short description of PM processes as well as an industry overview was also presented in the appendix.

This roadmap followed a prospective market-pull approach. The PM industry has already established that they want to be the preferred source of near net-shaped and metal-based systems. This roadmap looks at what R&D is required to improve and maintain the production of the desired end product.

2.1.6.4. The South African Aluminium Industry Roadmap (2016-2030)

In March 2017, South Africa produced the South African Aluminium Industry Roadmap (SAAIR). South Africa has been involved with the aluminium industry for more than 70 years and the country would like to maintain and develop this industry even further. Globally aluminium metal has been identified as an important material of the future and the roadmap under discussion highlights the benefits the country would have by improving and growing the local aluminium industry (SAAIR, 2017).

The objective of the SAAIR is to act as a strategic guide in taking the aluminium industry into the future. South Africa has no aluminium minerals to mine but has created a downstream processing industry. Aluminium oxide (alumina) is imported (mostly from Australia) and processed locally. For most markets the semi-fabrication, fabrication and final product manufacturing process of aluminium are generic across the globe. The result is that for any industry to remain relevant it must always consider new market requirements that are driven by the consumer revolution. This requires constant modernisation and maintenance for a process and a country to remain relevant. The long-term aim for South Africa is therefore to establish an industry that is capable of sustainable world class advanced manufacturing using aluminium.

The roadmap was started with a workshop consisting of a steering committee of industry leaders to determine the vision for the industry. The vision was created to address social wellbeing, industry growth, competitiveness, efficiency, optimisation, unique products and the markets while also considering exports. The visioning workshop was followed by regional roadmapping workshops composed of experts from various fields in the industry. This roadmap was compiled using a customised industry roadmap model based on best practice, outlining market sub-sectors, final products, processes, knowledge, complements, dynamic capabilities, platforms and ecosystems. The roadmap was then reviewed and tested.

The vision of the roadmap was created by doing “mind-time travel” into the future. In this future thinking approach, barriers, possibilities and drivers that might affect the future South African Aluminium Industry were identified. This was done by the steering committee under strong facilitation in the visioning workshop. Future thinking also included what the future landscape would look like when incorporating emerging technologies and the future behaviour of people and predictable and unpredictable events. Several vision elements were identified, and these acted as beacons for the roadmap design. The vision elements also informed the strategies and policies that need to be in place in order to the vision to be realised. The identified vision elements were:

- competitive supplier of primary and secondary material,
- optimisation of resources,
- grow capacity in the industry,
- energy-efficient sustainable and environmentally friendly,
- significant job creation, socioeconomic upliftment and resultant well-being for communities,
- unique own finished products,
- include regional and global markets, and
- grow to net exporter through import replacement and localisation.

After the identification of the vision, details of the roadmap (identified during the expert workshops) were visualised for a timeline starting at the current situation and roadmapping the scenario from 2016 to 2020, and then from 2020 to 2030. Visual roadmaps were created for the factors identified earlier: outlining market sub-sectors, final products, processes (established and being researched), knowledge (R&D), complements, dynamic capabilities, platforms and ecosystems.

The current and future activities along the aluminium value chain were graphically illustrated. From an environmental perspective, the roadmap considered development policies and mentioned the gain and drive to reduce the carbon footprint (reduced emissions). Except for CO_2 reduction, mention was made to the recycling of water, the minimisation of waste generation, energy efficiency, recycling of used materials and the responsible sourcing of raw materials from environmentally friendly suppliers. The roadmap also discussed the socio-economic effect that the development of an aluminium industry would have on the country in its conjectural context. The roadmap stated that new jobs will be generated through employment and opportunities for small businesses. An increase in employment as well as input from infrastructure investment will lead to overall employee wellbeing, education, improved services, sustainable housing and community engagement. Overall, the establishment of the aluminium industry will lead to a growth in the country's gross domestic product (GDP) as the industry grows.

The desired end product would be advanced manufactured aluminium products. This roadmap therefore followed a market-pull approach as it started with the desired product and identified the required R&D needed to arrive at this product.

2.1.6.5. Aluminium Industry Technology Roadmap (North America)

In 2003 the Aluminium Association published the Aluminium Industry technology roadmap (The Aluminum Association, 2003). Correlating with the literature discussed earlier (in the roadmapping literature section) a goal or vision must be known in order to align the roadmapping process with the desired outcome. The vision of the North American aluminium industry was to be universally recognised by 2020 as a world leader in the aluminium industry. Areas identified that required technical solutions to achieve this vision were products and markets, sustainability and energy and resources.

Under products and market, the vision was to produce a superior value material that is tailored to customer needs, this will ensure product demand. Under sustainability, the vision was to understand and manage the economic, environmental and social dimensions that may arise to ensure a sustainable future. Under energy and resources, the vision is to work efficiently, reach the energy targets and to generate minimum waste.

The roadmapping strategy, produced by the USA Department of Energy in 2003, was outlined as an organised, strategic technology agenda (see Figure 6). What this agenda entailed was coming up with detailed, sector-specific performance targets, the identification of technical barriers and the identification of research and development needs/priorities for different process-based sectors (The Aluminum Association, 2003).

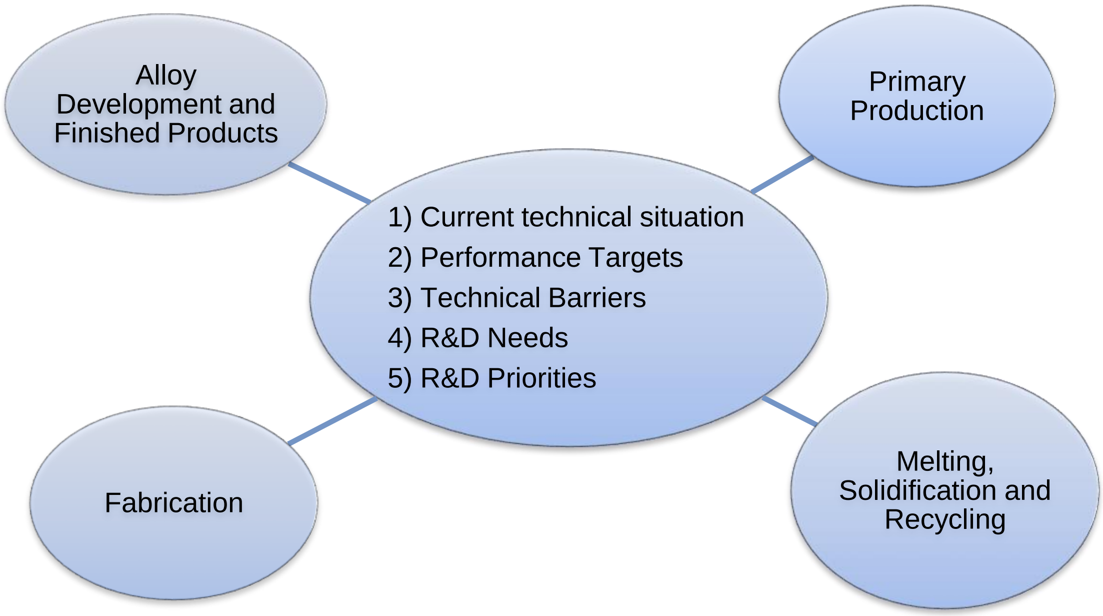


Figure 6. Format for developing an aluminium industry (Source: The Aluminum Association, 2003).

In this roadmap each of the main sectors (represented by small outside circles of Figure 6) were exposed to the outline of the agenda, first starting with the current technical situation. Each sector's performance targets were then discussed looking at the products and the markets, the energy and resources needed to achieve the goal as well as the sustainability of that sector. The final three points on the agenda looked at what technical barriers were being experienced and what R&D was needed and should be prioritised. To ensure the successful implementation of the aluminium industry roadmap a strategy for the way forward, called the implementation strategy, was provided (see Figure 7).

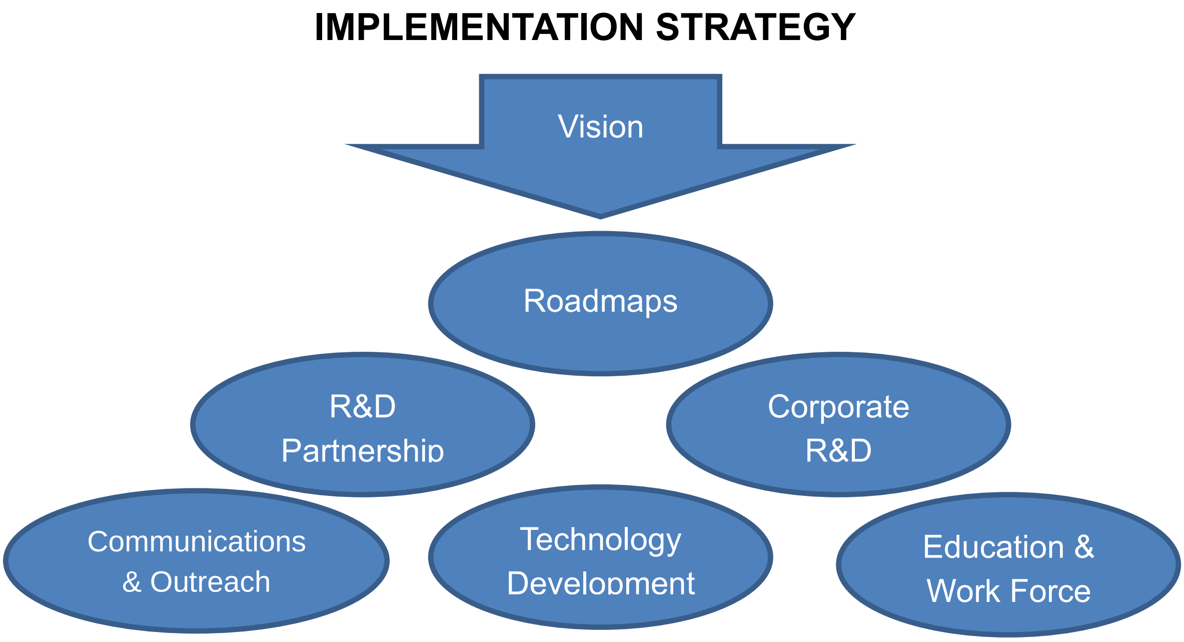


Figure 7. The implementation strategy of the aluminium industry (Source: The Aluminum Association, 2003).

The implementation strategy required collaborative partnerships between all stakeholders. This is because the industry goals are not only dependent on the four sectors mentioned above, but also linked to broader multi-disciplinary sectors. This includes aluminium producers, equipment suppliers, research laboratories, governmental programs as well as other research institutions. This implementation strategy has proven efficient for the aluminium industry and sustainable progress has been reported over a long-term.

The aluminium industry technology roadmap followed a market-pull approach. The North American aluminium industry recognised the potential aluminium products have in the industry and wanted to ensure that their R&D plan would allow them to keep on producing the desired end product as a universally recognised technology leader.

2.1.6.6. Canadian Aluminium Transformation Technology Roadmap

In 2006, the Canadian aluminium industry noticed that it was losing its position as one of the world's top 10 aluminium producers of rolled products. This roadmap was produced in response to that realisation (RéseauTrans-Al, 2006). This realisation came 6 years after the country produced its first aluminium industry roadmap to guide the growth of the industry. The predicted reason for the country to be losing its effectiveness within the aluminium industry could be ascribed to the growing production rates in for example China. Canada therefore called for an adaptation of its first roadmap (released in 2000) to encourage manufacturers to invest in leading-edge design and manufacturing technologies instead of outdated traditional technologies.

The 2006 Canadian aluminium roadmap goal/vision was to provide the Canadian aluminium transformation industry with information on global market trends and to identify technologies that could create wealth by making the Canadian aluminium industry a major competitor.

Prior to compiling the roadmap, industry experts identified seven main sectors where the aluminium industry could be effective. The experts identified and analysed a set of 38 opportunities under the top seven headings within the development sectors. The roadmap released by the Canadian aluminium industry in 2006 was designed based on the mentioned opportunities. The roadmap was created to be a strategic tool to enable the Canadians to identify the future aluminium needs and to plan towards satisfying the needs while generating wealth for the country.

The roadmapping strategy used by the Canadians was divided into four phases:

- The first phase consisted of generating a plan that included a preliminary study, to create a committee, to obtain funding and to compile a competent team.
- The second phase was the application of roadmapping principles such as data collection, obtaining specialist opinions, identifying the possible opportunities and technologies, workshops as well as a survey.
- The third phase consisted of combining the newly gathered information (from workshops, research, experts and the survey) into a final draft. From the specialist feedback, priority ratings were obtained that assisted in identifying the most promising opportunities.
- The fourth phase was named "Promotion" and entailed the implementation of the roadmapping tool developed by the first three phases.

This roadmap provided a detailed overview of the existing aluminium industry with elaboration on primary and secondary aluminium production, semi-finished products, manufacturers and specialised equipment suppliers, finished products by market type and lastly the aluminium industry technology platforms. This roadmap was more interactive (through survey and workshops) that allowed the identified opportunities to be prioritised. Specific opportunities (out of the 38) were highlighted as the "most likely" to stimulate the aluminium transformation in Canada, but the report also allowed the authors to make informed recommendations (RéseauTrans-Al, 2006).

Although a committee to drive the roadmap and its resultant recommendations was established at the first phase of the roadmapping process, a definite gap in implementation can be observed compared to countries with a more established aluminium industry (such as the USA). From the recommendations it can be concluded that the industry is not fully integrated with the R&D sector and improved integration was recommended. Other recommendations included promoting training within the industry and updating the roadmap on a continuous basis.

This roadmap followed a prospective market-pull approach. The Canadian Aluminium industry was already developed, but the technologies being applied were outdated resulting in the industry becoming irrelevant. To prevent this from happening the Canadian aluminium industry encouraged technological innovations and R&D to allow the industry to arrive at the desired end product and remain relevant to the market.

2.1.7. Conclusion drawn from analysing the relevant industry roadmaps

Analysing the six identified roadmaps revealed similarities and differences used in industry to construct industry technology roadmaps for light metals in general. The broad classification of the six roadmaps is technology roadmaps for light metals which includes both titanium and aluminium. The purpose of investigating and analysing these light metal industry roadmaps were to build a checklist that indicates the most common roadmap layout applied to this field. It was decided not to elaborate on the combined layout developed from analysing the six industry technology roadmaps in the literature section. This layout will be presented and discussed in Table 9 in Section 3.1.2 and in Table 13 in Section 4.4.1 as it was created from the literature reviewed for this thesis and is therefore rather considered an output from this research than an input from reviewed literature.

The proposed layout (guided by the checklist) will be used in this study (academic rather than a working industry document) as a dialog or communication for the titanium metal industry. According to Carvalho, Fleury and Lopes (2013) this communication is usually more important than the final roadmap.

2.2. Introduction to the Titanium Metal Value Chain

The focus industry for this research is the titanium metal industry. This research aims to produce a roadmap that will guide South Africa to further develop this industry. The titanium industry is more complex than the iron and steel or even the aluminium industry, mainly due to the difficulties associated with processing the titanium to a pure metal as it is highly reactive (Tarselli, 2013). In addition, the titanium industry is highly fragmented adding to the complexity.

A value chain is a set of activities needed in making and selling a specific product. Each stage of the titanium value chain along with the production and processing of that specific stage will be discussed in more detail in the results section of this dissertation, but in order to design a suitable roadmap for this industry, the titanium metal value chain needs to be introduced. Titanium is mined as an enriched ore that undergoes several beneficiation stages to produce a finished titanium product. All of the stages can be covered in three main sections namely raw material, the processes and technologies, and finally finished products for the market (Du Preez, Damm and Jordaan, 2013).

The three mentioned sections can be sub-divided into eight production stages. Each stage is dependent on its specific precursor that in turn is needed to produce the product for the next stage. The titanium metal value chain and is displayed in Figure 8. This value chain follows the most common global titanium metal value chain stages (observed from literature) but was designed specifically for this research by the author of this thesis. The dotted lines indicate alternative routes that can be followed to produce the final stages, which are mill products and powder products (Figure 8). The value chain presented in Figure 8, as well as some of the conclusions in this section were summarised in an article written in conjunction with this research (Roux, Van der Lingen and Botha, 2019).

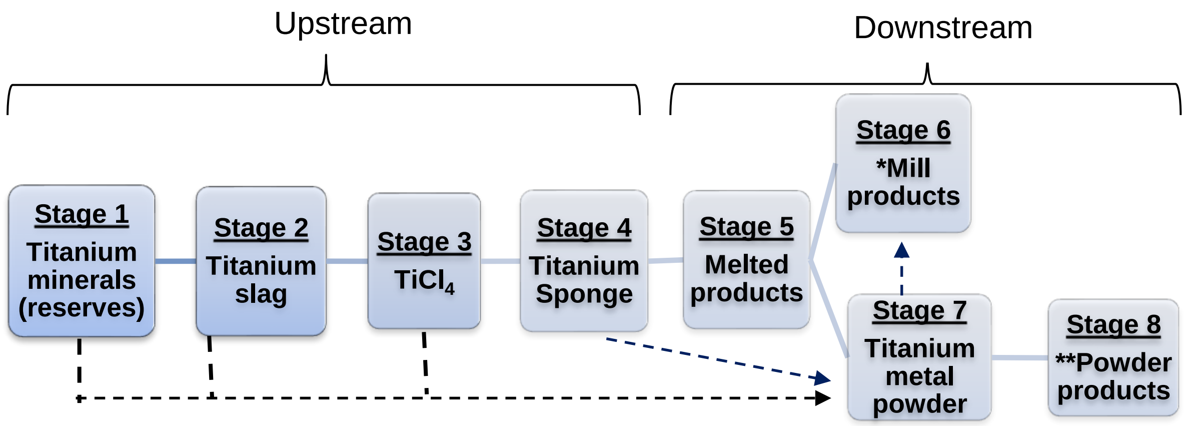
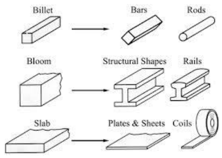
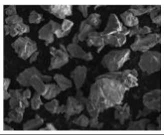
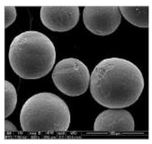


Figure 8. The titanium metal product value chain (Source: Roux *et al*., 2019). *It is important to note that when referring to mill products in this thesis it will not only include intermediate mill products produced from melted products, but also products fabricated from intermediate mill products referred to as final mill products. ** Powder products refers to products made from titanium metal powder.

Figure 8 illustrates the eight identified stages of the titanium product value chain. Stage 1 represents the mining of the titanium minerals or the titanium reserves. Stage 2 entails the production of titanium slag by upgrading/purifying the natural raw minerals containing titanium. Stage 3 is the production of titanium tetrachloride ($TiCl_4$) which is the liquid precursor for both titanium pigment and titanium metal production. Stage 4 is the production of titanium sponge which is, to an extent, a form of pure titanium metal. Stage 5 is the production of melted products in the form of ingots, blooms, billets and slabs which are processed forms of titanium sponge. Stage 6 is the production of mill products which could either be final or intermediate products. Stage 7 is titanium metal powder which is also a solid form of titanium metal. Stage 8 is the production of products from titanium metal powder (Roux *et al.,* 2019).

Table 8. Illustration of the products from each stage of the titanium metal value chain (Sources: Paton, Trigub and Zhuk, 2008; Menezes, Reeves, Kailas and Lovell, 2013; Roskill, 2013; Wang, Li, Hua, Zhang, Zhang and Ke, 2014; Oosthuizen and Swanepoel, 2018).

Stage	Name	Visual
1	Titanium mineral (reserves)	 
2	Titanium slag	 
3	$TiCl_4$	 
4	Titanium sponge	 
5	Melted products	 
6	Mill products	 
7	Titanium metal powder	Angular:  Spherical: 
8	Powder products	 

Both Figure 8 and Table 8 indicate the complexity of processing that occurs between stage 1 and stage 8 of the titanium metal value chain. The production stages do not occur on the same site and often not within the same country. The result of this is that the titanium product value chain is fragmented as will be discussed in the next section (Cardarelli, 2013; ILUKA, 2019).

Applying a roadmap to a value chain has proven historic benefits as indicated by Fine (2004) who elaborated on the application of value chain roadmapping on the struggling global communications industry as well as for advancing the semiconductor industry. Although the context and objectives of both these industries differ from the titanium metal industry it can be useful to reflect on the roadmapping process based on a value chain approach. The communication industry was struggling because of major changes that occurred due to rapid evolution within the industry.

The main benefit discussed by Fine (2004), for applying a value chain to roadmapping, is that the development risk was lowered for each supplier as each could invest in a single development project along the value chain. This was true for both the communication and semiconductor industries. Linking this value chain roadmapping to the South African titanium metal industry, each of the identified value chain stages are dependent on its specific precursor that in turn is needed to produce the product for the next stage. In a fragmented value chain a specific stage could exist independently of its precursor and successor (based on geographic manufacturing of that stage) meaning that the development risk for the supplier of a specific stage is lower as investment would be limited to that stage and not to the success of the complete titanium metal industry value chain. This indicates that the principle of roadmapping over a value chain can be applied to the South African titanium metal industry.

2.3. The Fragmented Titanium Value Chain

Production fragmentation is the geographical separation of activities involved in producing either goods and/or services across two or more countries (Athukorala and Yamashita, 2007). The trade within production fragmentation differs from standard trade which is based on the exchange of goods that are produced (start to finish) in one country (Athukorala and Yamashita, 2007). In the late 1960s, the concept for international production networks were developed when cross country production within the clothing and electronics industries were established. Since then, product fragmentation has spread into almost any imaginable field with the major trade benefit being the reduction in production costs mainly in the form of low labour cost (Athukorala and Yamashita, 2007; Belussi and Sedita, 2010). Figure 9 illustrates production fragmentation of the components for a Boeing 787 Dreamliner.

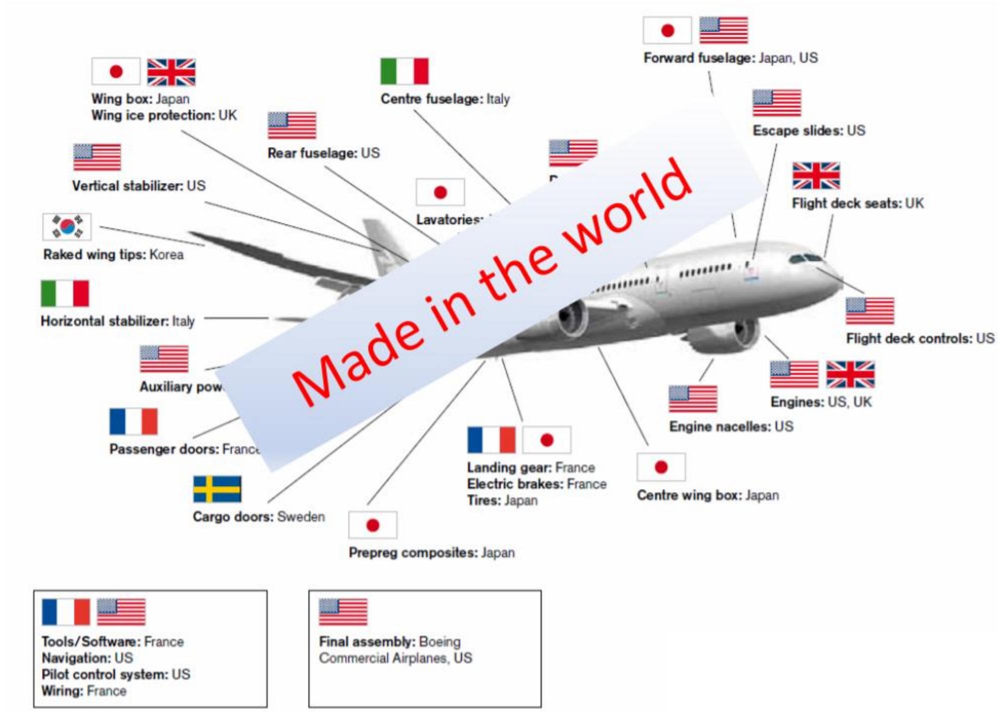


Figure 9. Indication of where the different parts of a Boeing 787 Dreamliner is made - fragmentation of production (Source: Meng and Miroudot, 2011).

Since the establishment of production fragmentation, outsourcing and global competition have caused international trade and intermediate product exchanges to grow significantly, exceeding the trade of final goods (Belussi and Sedita, 2010). This growth in trade is related to the parts crossing borders several times before they are complete (Athukorala and Yamashita, 2007). Another benefit introduced with the fragmented global value chain is the establishment of links and integration of economies within developed and developing countries. International fragmentation is easily achieved by a multinational enterprise (MNE) building a subsidiary abroad to replace local functions (Athukorala and Yamashita, 2007). This fragmented network can then further evolve as host businesses start to compete for work. The work can then be subcontracted to host-country firms which should comply to the production details set by the developed country (Athukorala and Yamashita, 2007).

Limited research is available on the titanium industry operating on a fragmented value chain. Cardarelli (2013) is one of the few that directly discusses the titanium industry as having a fragmented value chain. For Cardarelli (2013) the fragmentation of the value chain within the titanium industry was prominent in the amount of small companies located far from the consumption market. For the titanium industry there are a few main factors causing fragmentation. Six of the main reasons identified in this research by Roux *et al*. (2019) are:

- complexity of the metal production process,

- purity of the mineral feedstock,
- environmental concerns,
- availability of technology,
- distance to the market, and
- absence of economic titanium reserves.

Economic quantities of titanium minerals reserves do not guarantee that a country will have a thriving titanium industry (Abkowitz *et al*., 1990). More than 15 countries are mining titanium with the top five countries, by quantity, being Australia, Canada, China, South Africa and Mozambique (Dewhurst, 2013; USGS, 2018). Titanium minerals occurrence and mining (stage 1) as well as mineral upgrading (stage 2) are globally seen as common and established processes as these first two stages are straight forward and could easily be established in countries that possess economic quantities and qualities of titanium reserves (Roux *et al.*, 2019).

The first stage in the value chain where the fragmentation is mostly observed is stage 3, the production of $TiCl_4$ through the chloride process. The bulk of the $TiCl_4$ produced is used in the production of titanium pigment and a smaller portion of high quality $TiCl_4$ is used to produce titanium metal (Van Vuuren, 2009a; Van Tonder, 2010). Two or the top titanium mining countries that fall victim to the fragmented titanium metal value chain at this stage are South Africa and Australia (USGS, 2018). Australia processes most of their titanium to produce pigment and exports the rest for further processing. No $TiCl_4$ is produced in Australia that could be used for the production of titanium metal (GeoscienceAustralia, 2019). South Africa, likewise, does not produce any $TiCl_4$.

The fourth stage (stage 4) of the conventional titanium metal value chain incorporates the Kroll process (as the dominant process). The Kroll process is the leading commercial process (produces ±99 % of the global titanium metal) for the production of titanium metal and is therefore referred to in literature as the conventional titanium production method (Nagesh *et al*., 2004; Van Tonder, 2010). Over the years several other processes have come and gone with advancements on the Kroll process keeping it at the number one titanium metal producing position. Globally only seven countries are actively producing titanium sponge namely China, Japan, Kazakhstan, Russia, USA, Ukraine and most recently Saudi Arabia (Dewhurst, 2013; Asian Metal, 2014; Roskill, 2019). Important to note from these sponge producing countries is that Russia, Saudi Arabia and Japan mine little to no titanium ore for sponge production (USGS, 2018). Russia for example has low quality titanium reserves and only a small portion of local ilmenite production. For the rest of its titanium mineral supplies the country is reliant on imports (TZMI, 2012).

Not a lot of academic literature is available specifically on countries that participate in stage 5 (melted product) and stage 6 (mill products). The top countries for mill product output in 2017 were China, USA, Russia, Japan and Europe (countries in Europe not specified) (Roberts, 2018). According to the 2019 Roskill report the production of sponge and the subsequent melted product step is mostly done on the same site (Roskill, 2019). Once the sponge is processed into titanium melted product it can be shipped anywhere in the world for further processing, but the 2019 Roskill report also stated that the limited melted product trade was observed globally as they mostly get further processed to mill products (stage 6) on the same site or in the same country (Roskill, 2019).

Stage 7 within the titanium metal value chain is the production of titanium metal powder. This could either be from crushing down sponge (conventional), or from the direct powder production route. The global leading titanium metal powder producers are USA, China, Japan, and Europe (QY Research Group, 2017). The bulk of titanium metal powder is produced from sponge and the most popular processes used are Hydride-dehydride (HDH), gas atomisation and plasma-rotating electrode (PREP) (Oh *et al*., 2014). Countries currently producing titanium powder from titanium sponge are USA, Japan, China, Russia, Australia, Ukraine, Canada, France, Germany, Sweden and the UK (Moxson, Senkov and Froes, 2000; QY Research Group, 2017; Roskill, 2019; Titanium Institute, 2019).

The direct production of titanium metal powder has been identified as a viable way to reduce the high production cost of titanium metal (Bolzoni, Ruiz-Navas and Gordo, 2017). This cost reduction can be attributed to two main aspects. The first aspect is by the direct reduction of the host mineral or an intermediate precursor (titanium tetrachloride) to form titanium metal powder (Roskill reports, 2013). The second aspect is related to a reduced cost for processing and manufacturing of the powder compared to the conventional metallurgical route (Bolzoni, Ruiz-Navas and Gordo, 2017). The leading country that produces titanium metal powder directly (not from titanium sponge) is the USA through the Armstrong process. The Armstrong process is a chemical (metallothermic) production route. In this process $TiCl_4$ is reduced using alkali metals such as sodium. In 2019, the Armstrong process had the capacity to produce 1 800 tonnes per annum (Roskill, 2019). In addition to the chemical route titanium powder is also produced directly (not from sponge fines) following the electrochemical and atomisation routes. Several other countries are devoted to develop a method to produce titanium powder following direct routes instead of first producing sponge (Whittaker, 2012).

The last and final stage of the titanium metal value chain (stage 8) is the production of a finished product from titanium powder, hence a powder product. The process of producing a part from a powder is called powder metallurgy (PM) (EPMA, 2018).

This process is an innovation that allows for a reduced cost as well as improved performance of the part while shortening the development and production cycle times (Gabriele, 2018). One of the leading developments within stage 8 of the titanium metal value chain is regarding AM. Similar to the trend obtained for mill products, it is difficult to track which countries produce titanium powder products as various technologies to produce powder products are available. Titanium powder is readily available on the market and is used in several industries, such as the aerospace, medical, chemical and automotive industry (QY Research Group, 2017).

2.3.1. Upgrading of fragmented value chains

Tang et al. (2009), refers to a fragmented value chain as having a local segment within the global value chain. The authors' focus was on applying an industry technology roadmap to fragmented industries in China to promote industrial upgrading or in a simpler term, upgrade the local value chain within several Chinese industries (ceramic, green lead-free and aluminium). This approach is similar to what the author of this thesis intends to accomplish if the research indicates that the local South African titanium metal value chain should be upgraded. In the context of this research upgrading refers to a value chain becoming less fragmented.

Both South Africa and China are developing countries competing against the high entry barriers established by developed countries and regions (R&D, marketing and sales). These barriers enhance the advantages provided by resources and capabilities such as access to technology and ownership of intellectual property making it even more difficult for developing countries to enter the market. The result is that developing countries must enter the value chain through lower entry barriers which often have more fierce competition and unequal distribution of income (Tang et al., 2009).

Entry into the value chain is an important step towards contributing to the global value chain under discussion, but for a developing country to ensure progress and eventually upgrading its presence in the global value chain these countries need to ensure that improvements are applied to their indigenous innovations. This should be done through industrial upgrading through innovation to enhance the capability of value creation and value acquisition (Tang et al., 2009).

Similar to the South African titanium metal industry, the example provided by Tang et al. (2009) indicated that fragmented industries in China became dependent on foreign technologies and that low advancements of indigenous innovation capabilities were observed. This resulted in a low level of absorptive capacity and a high level of foreign technology dependence. Tang et al. (2009) therefore recommended the application of technology roadmapping to identify critical technology trajectories as well as coordinated R&D activities to address the issue on industrial upgrading. Some points considered by Tang et al. (2009) that will also be incorporated into considering to upgrade the South African titanium metal industry are listed below:

- Identify and acquire new technologies
- Accumulate absorptive capacity through assimilation and improvement of local technologies
- Constantly seek to explore emerging technologies
- Perform forward looking predictive analysis of value chain upgrading
- Allocate the needed technology resources optimally
- Analyse past evolution paths, current situations and future development trends
- Establish short-term, mid-term and long-term value chain upgrading goals
- Select feasible value chain paths based on information gathered

2.4. Chapter Summary

Chapter 2 predominantly includes a discussion of roadmap literature. This is because detailed literature discussions are given in the chapters concerning the titanium value chain stages. The chapter starts out by introducing roadmaps as a tool that links technological innovations, policy as well as business and social drivers. The tool was first used in 1970 by the former chairman of Motorola but has since become common practice especially by governments, international organisations, industrial bodies, science councils and companies.

Next the different types of roadmaps were discussed. Roadmapping is becoming more and more flexible leading to the development of several different roadmap types for several purposes. Together with the complexity of roadmap types, the classification of these roadmaps is becoming difficult and several classification systems are available. To narrow this down a literature survey indicated that the classifications from three main sources were the most used. These classifications were presented by Phaal, Farrukh and Probert (2001), Kostoff and Schaller (2001) and Haddad and Maldonado (2017).

The literature indicated that the link between different roadmap types is vague and over-laps common. EIRMA (2017) provided the first attempt to simplify roadmap design by presenting a generic roadmapping layout that incorporated a time-based chart and consisted of several layers. The most used layers are market, product, technology, R&D, and resources. The expanded version of this generic roadmap added three questions namely “Where are we now?”, “Where do we want to go?”

and “How do we get there?”. This roadmap enables a view of the markets, products and technologies over a selected time period in an organised and simplified manner.

The literature also discusses the different roadmapping analyses that could be used namely prospective (looking forward form the current position and consider what is required for future direction) and retrospective (start with a final product and work backwards). Both these analysis types could then follow either a technology-push (a new technology that drives development of a new product) or a market-pull (start with the desired end product and identify required R&D) approach or a combination of the two.

Another important aspect covered under roadmap literature was the construction of the roadmap vision. The vision should be the driver of the roadmap and for the previously mention questions this is the “Where do we want to go?” part of roadmapping. The literature indicated that the vision creation is flexible as there is no set way to establish a technology roadmap vision. There however, is an industry standard that recommends the input from industry experts that can be obtained from visioning workshops, conducting interviews or through surveys.

The preferred roadmap type selected for this research was discussed in more detail, i.e. the industry technology roadmap. The main reason for selecting this roadmap type was that it focuses on foresighting the development, commercialisation and deployment of new technologies. These are required to develop a roadmap for the local titanium metal industry.

The final roadmapping section in the literature survey section presented case studies of several industry technology roadmaps developed for related industries (light metals). A total of 13 roadmaps were obtained and six of these roadmaps were analysed as working examples for industry technology roadmaps. The selected roadmaps were the closest related to the South African titanium industry as they were either applicable to South Africa or made mention of titanium. The aim of analysing these roadmaps were to map the document layout that will then be used as a guide for the roadmap produced for the current study.

The literature survey then addressed the titanium metal value chain to set the context of the study within the titanium field. This value chain consists of eight value chain stages that start at the raw material (titanium minerals) as stage 1, titanium slag (an upgraded ilmenite products) as stage 2, $TiCl_4$ as stage 3, titanium sponge as stage 4, melted products as stage 5, mill products as stage 6, titanium metal powder as stage 7 and powder products as stage 8. Finally, the literature survey discussed the fragmentation within the titanium value chain. Fragmentation is the geographical separation of activities to produce goods and services and this is observed on a global scale within the titanium metal industry.

3. Chapter 3 – Developing a Conceptual Model

3.1. The Roadmap Model

Several roadmapping models are available and the different types of roadmaps were discussed in Chapter 2. In order to create a roadmap specifically suitable to the South African titanium metal industry, a novel roadmapping element was introduced. This element took the fragmented nature of the titanium industry value chain into consideration.

3.1.1. Selecting the Roadmap Type

When considering the aim of the South African titanium industry (which is to grow the local titanium industry) and the definitions and benefits of the different types of roadmaps, the most suitable type of roadmap is a technology roadmap and more specifically an industry technology roadmap. This roadmap type was selected as it focuses on foresighting the development, commercialisation and deployment of new or future technologies. South Africa's titanium metal industry value chain has several gaps that could only be filled by this proposed new technology.

The selected roadmapping approach for this research was a prospective market-pull approach. Prospective because the South African titanium industry is looking from its current position and considering what is required for future direction. The titanium industry is highly competitive with a few countries dominating the global trade (USA, China, Japan and Russia) of titanium products. For South Africa to be able to create a global presence within this market the country would have to be able to compete with these countries in the selected value chain stages. This competition would be for internal and external trade as the cost to import certain value chain stage products might be cheaper from other countries e.g. China compared to local production. For the local industry to be competitive the South African government might have to initially implement initially additional import tax and export incentives. The market-pull approach would therefore ensure that the country only develops stages of the titanium metal value chain that are able to compete on a global scale. From Figure 8 only four stages of the value chain are functioning on industry level in South Africa. Two of these stages fall within the upstream and two within the downstream processing stages. Figure 10 indicates the existing stages with the gap that needs to be filled by applying a market-pull roadmapping approach.

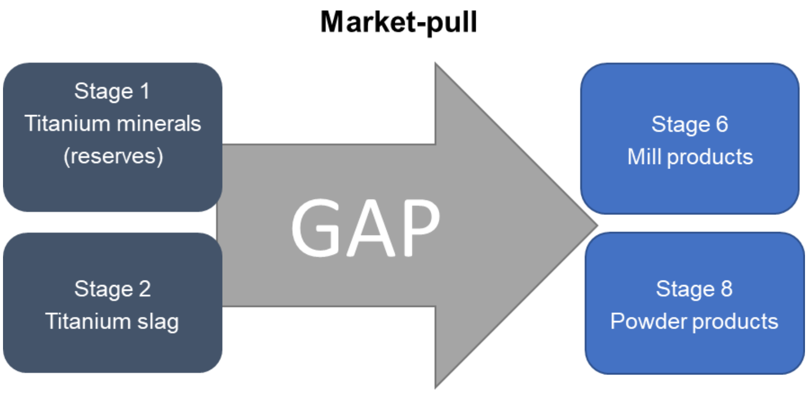


Figure 10. The prospective market-pull approach for South Africa.

A market-pull approach will start with the established downstream processing companies. These companies already have an established market, but due to the fragmented nature of the titanium industry value chain, South Africa does not have the technological capability to produce the titanium metal required by these companies. This approach would therefore identify the technologies needed by these companies to improve on the downstream processing while remaining innovative and competitive. This approach would ensure that South Africa produces products for an existing market and that the R&D is in line with the product aimed to be produced.

To date the South African government has developed the titanium metal industry using a technology-push approach. For the upstream industry side, a technology-push approach was taken for the development of the Aeroswift machine. This technology was designed before a clear market was defined and the technology was a first globally. Local R&D also being driven by technology-push approach is the research on $TiCl_4$ production and titanium powder production. Locally there is not a big enough local market for a $TiCl_4$ production facility, but there is a surplus of feedstock minerals. Therefore, a technology-push approach was followed whereby the aim was to produce a technology due to the first stage of the value chain (mineral feedstock) being abundant and not due to the market demand. The powder production technology also follows this approach as the R&D is focusing on producing a new technology for an unknown market.

3.1.2. The Industry Technology Roadmap Model Design

The proposed roadmap model will be a combination of the generic technology roadmapping multi-layered layout and the key aspects compiled from investigating actual industry technology roadmaps. The generic technology roadmap multi-layered layout was discussed in detail in Section 2.1.2 and is illustrated in Figure 1 and Figure 2. This generic layout indicates that all roadmaps should consider five main layers namely market, product, technology, R&D and resources. These layers should then be approached by applying fundamental questions that ask, “Where are we now?”, “Where do we want to go?” and “How do we get there?” Lastly this should be done with considering a timeframe and the fundamental question for time being “When should this happen?”.

The second input for the proposed roadmap model was obtained from studying the key aspects confined in the layout of six industry technology roadmaps. These roadmaps were discussed in the literature in Chapter 2, Section 2.1.6. Three of these roadmaps were on the aluminium industry and three were on sub-sections within the metal industry (two on additive manufacturing and one on powder metallurgy). The three roadmaps on the sub-sections of the metal industry made small, but relevant mention of the titanium metal industry. In a comparison between these roadmaps, Table 9 was compiled to identify key aspects that were listed in most roadmaps.

Table 9. Key aspects observed from industry technology roadmaps (Phases 1 to 4 are mentioned by Londo *et al.*, 2013).

Key aspects for industry roadmaps	**A South African Additive Manufacturing Strategy**	**Additive Manufacturing Technology Roadmap for Australia**	**Technology Update for the Powder Metallurgy Industry. PM Industry Roadmap**	**South African Aluminium Industry Roadmap (2016-2030)**	**The Aluminium Industry Technology Roadmap**	**Canadian Aluminium Transformation Technology Roadmap**
Timeframe	2014-2023	2011-2015 & 2015-2025	2012-2021	2016-2030	2003-2020	2006-2016
Analysis type	Market-pull	Technology-push	Market-pull	Market-pull	Market-pull	Market-pull
Discuss Phase 1: Planning & prep.	Yes	Yes	No	Yes	Yes	Yes
Discuss Phase 2: Visioning	Yes	Yes	Yes	Yes	Yes	Yes
Discuss Phase 3: Roadmap development	Yes	Yes	No	Yes	Yes	Yes
Discuss Phase 4: Roadmap implementation, monitoring, revision	Yes	Yes	Yes	Yes	Yes	Yes
Build on previous Roadmap(s)	No	No	Y	No	Yes	Yes
Workshops were held	Yes	No	No	Yes	No	Yes
Discussed the current situation	Yes	Yes	Yes	Yes	Yes	Yes
Cover global sector	Yes	Yes	Yes	Yes	Limited	Yes
Cover global markets	Yes	Yes	Yes	Yes	Limited	Yes
Sufficient graphics and illustrations	No	No	No	Yes	Limited	Yes
Prioritisation or rating processes	Yes	No	No	No	Yes	Yes
Established R&D structure already exist in country	Yes	Yes	Yes	Yes	Yes	No
Mention energy consumption	No	Yes	Yes	Yes	Yes	Yes
Discuss sustainability & socio-economics	Yes	Yes	No	Yes	Yes	No
Comments	None	Layout was in chapter form	This is a follow-up roadmap	Future thinking was used	None	Limited by pre-determined opportunities

Table 9 was compiled by investigating six industry technology roadmaps and finding correlations between key aspects within all of the roadmaps. Most of the roadmaps presented the same four phase structure as used by Londo *et al.* (2013). These four phases are planning and preparation, visioning, roadmap development and roadmap implementation, monitoring and revision. As these four phases have been identified in most of the roadmaps investigated, it will be applied to this study and will be used together with the generic technology roadmapping structure for the South African titanium metal industry roadmap.

In addition to the four roadmapping phases other correlations observed between the roadmaps are displayed in Table 9 with an indication on whether each of the investigated roadmaps considered them. The most prominent and consistent correlations will be used for the roadmap design of this study and will be explained in more detail within the methodology section of this research (see Table 13 in Section 4.4.1).

3.1.3. Addressing Fragmentation within the Titanium Metal Value Chain

Based on the fragmented nature of the titanium metal industry value chain the result section of this thesis was divided into the eight identified stages of the titanium metal value chain. It should be noted that although there are eight stages of the value chain, only seven result chapters are presented as stage 1 and stage 2 (mineral reserves and slag production) were combined. These two stages were combined as they are mainly combined in industry on the same site and by the same company. Each chapter covers a stage of the titanium metal value chain and has its own literature review and roadmap visioning section (“Where are we now?” and “Where do we want to go?”). The reason for splitting the stages up into individual chapters was to indicate that when considering a fragmented value chain, each stage can be developed on its own if that was the identified need.

Using the generic technology roadmapping model as a guide, each stage of the titanium metal value chain was evaluated based on its latest (2019-2020) position and where experts believe the stage should go (future 2030). Under each stage the market, product, technology, R&D and resources were considered for both the now/current and the future plan. First the current stance of the value chain stages of the titanium metal value chain was identified, “Where is South Africa now?”. This was then followed by a stage specific vision (referred to as the vision element) or, “Where does South Africa want to go?”. Lastly an evaluation was conducted on how to get from the current position to where the industry wants to be, “How will South Africa get to the vision?”. A visualisation of the proposed roadmapping model created through considering the generic technology roadmapping layout is presented in Figure 11.

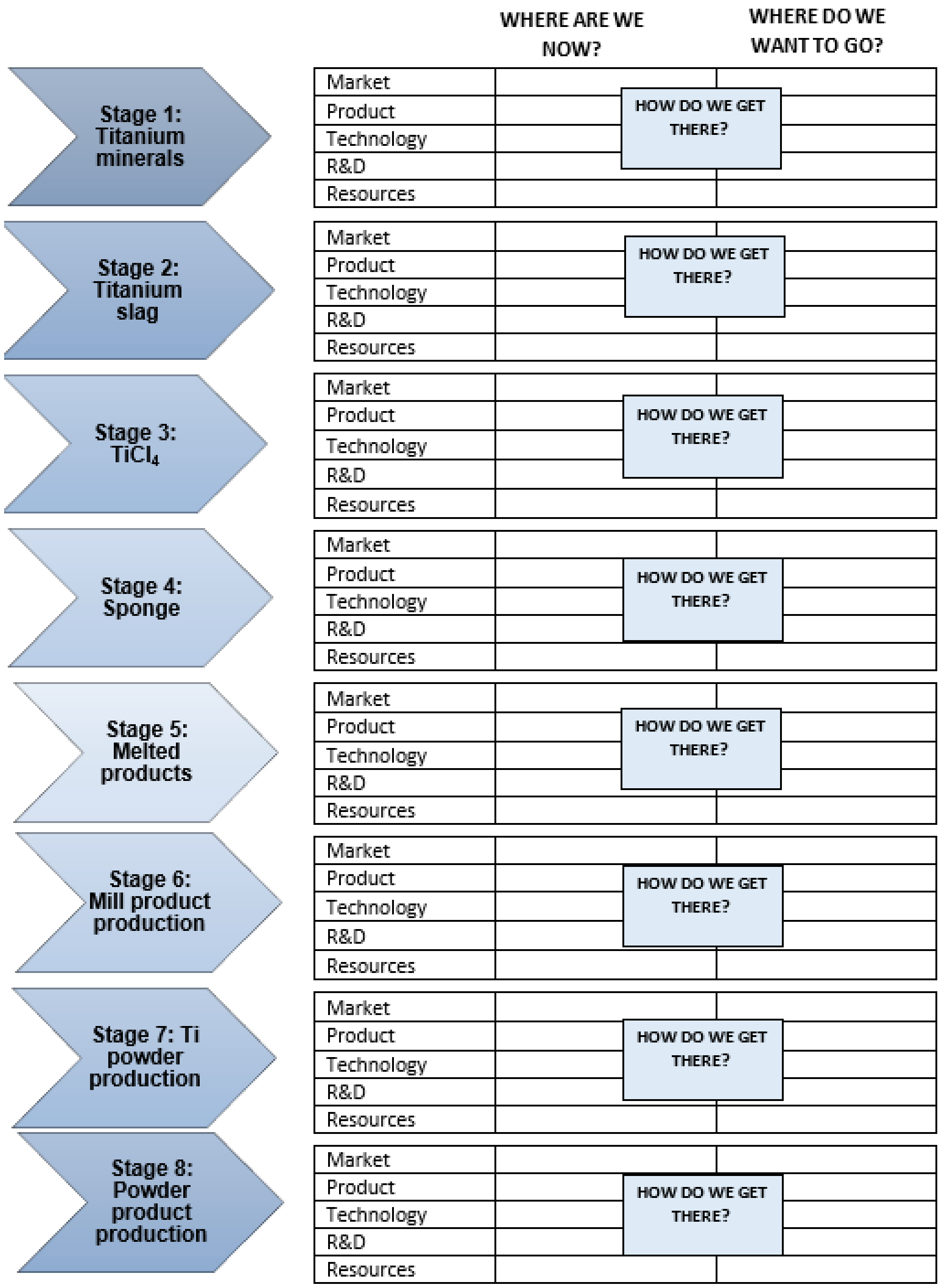


Figure 11. Applying the generic roadmapping model to the fragmented value chain of the titanium industry.

The roadmapping model was compiled for medium-term (three years up to 2023) and long-term (seven years up to 2030). The end product for combining the generic technology roadmap layout with the key aspects collected from Table 9 will be presented in Chapter 13 with the final South African titanium metal industry roadmap. The final roadmap would use a temporal approach to display the proposed South

African titanium metal industry technology roadmap as well as a full description following the logic of Table 9. The importance of a graphical representation has been emphasised in the literature review, but a roadmap also needs to be elaborated on with a proper narrative.

3.2. The South African Titanium Metal Value Chain

When applying the value chain introduced in Section 2.3, South Africa is involved in four of the eight value chain stages. These are stage 1 (mineral reserves), stage 2 (titanium slag), stage 6 (titanium mill products) and stage 8 (titanium powder products). The current status, regarding the development of the South African titanium metal value chain, is summarised in Table 10 the level/activity indicates whether the stage is operational in industry or only being investigated under R&D. The last column indicates the latest local developments within the identified titanium metal value chain.

Table 10. Current status of the South African titanium metal value chain (Source: Roskill, 2013; Kale and Hockaday, 2018; USGS, 2018; Roux *et al*., 2019).

Value chain stages	Level/activity	Development within South Africa
Stage 1: Titanium minerals	Industry & R&D	Globally South Africa has the fourth most titanium reserves.
Stage 2: Titanium slag	Industry & R&D	South Africa exports upgraded titanium slag and rutile.
Stage 3: $TiCl_4$	R&D	Local research on TiCl4 production is being conducted in South Africa, but no commercial plant has been established.
Stage 4: Titanium sponge	R&D	South Africa does not produce titanium sponge. Research on sponge (the Kroll process) has been undertaken in the past.
Stage 5: Melted products	R&D	Limited amounts of melted products are being imported. The country has limited melting capabilities.
Stage 6: Mill products	Industry & R&D	Several companies are machining imported ingots to sell final products on to the local or international market. South Africa is actively researching and developing this stage of the value chain.
Stage 7: Titanium metal powder production	R&D	South Africa has devoted more than 10 years of research to this stage and research is still ongoing.
Stage 8: Powder products	Industry & R&D	Several companies are fabricating specialised parts from titanium powder. South Africa is actively conducting research within this stage.

From Table 10 is observed that the South African titanium metal value chain is fragmented as some stage are established locally and some absent. The aim of this study was to produce a roadmap to guide the local titanium metal industry towards an improved global presence within the titanium metal industry. This will be done by identifying whether the absent stages of the titanium metal value chain should be pursued and where additional expansions are needed.

3.3. Applying the Model to the Fragmented Titanium Value Chain

One of the three sub-objectives of this study was to determine South Africa's position with regards to the global titanium metal value chain. The research question that accompanied the objective (question 7) was split into two questions pending the outcome of this research.

a. Should South Africa be active in the complete titanium metal value chain?

   OR

b. Should the South African titanium industry value chain remain fragmented?

No documented historic vision was found for the local titanium metal industry, but based on R&D the historic local vision could have been for South Africa to establish a complete titanium metal value chain locally. This research investigated the practicality of this while also considering the option for the South African titanium metal value chain to remain fragmented.

During the roadmapping process, this objective will be achieved by enabling each stage of the value chain to be self-standing. If a successive stage within the value chain is unable to be developed because its precursor has not yet been established in South Africa, then alternatives will be given for the stage to continue. Alternatives might include the establishment of new technologies or importing the needed material. Figure 12 indicates some of the alternatives. The green arrows represent exports from and red arrows imports into South Africa.

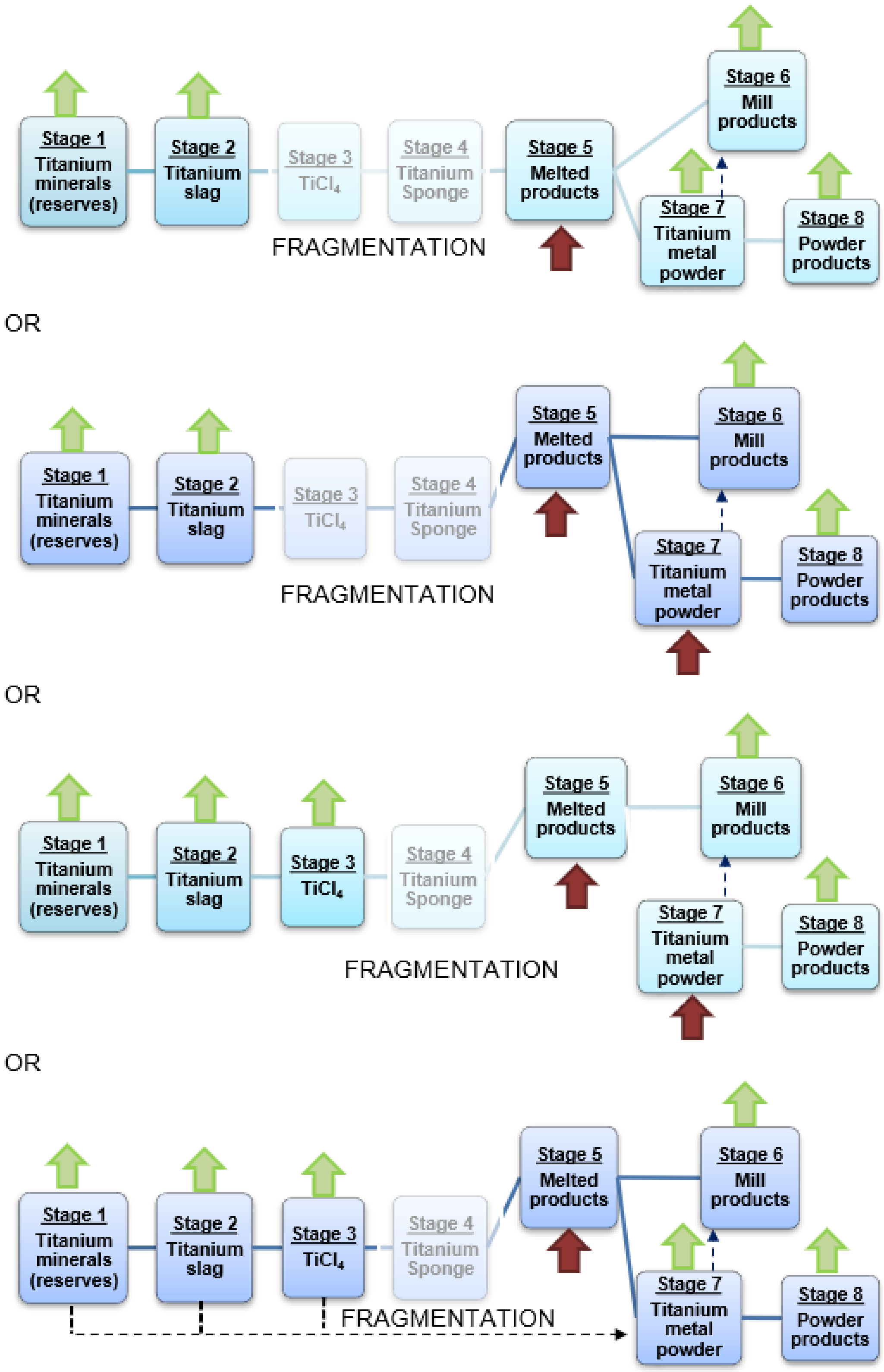


Figure 12. Alternative options for the South African titanium industry. The red arrows indicate imports and the green arrows exports.

Depending on the outcome of the research, a roadmap will be produced for the South African specific titanium metal industry. This roadmap would either indicate that the titanium metal industry value chain should remain fragmented or represent a complete value chain.

3.4. The Vision for the South African Titanium Metal Industry

It is known that the South African government has invested heavily to conduct research along the stages of a complete titanium metal value. From this perspective the roadmap's vision (non-official) should be to establish a complete titanium metal value chain within South Africa. A drive towards this vision has been pushed for more than 10 years and the progress to date needs to be evaluated and a new vision established.

The new vision should be obtained from interaction with industry and research experts to ensure a fresh perspective on what the South African titanium metal industry vision should be. This interaction will be the main source of data collection for this study and will be done by means of interviews and a survey.

Depending on the outcome of the expert interactions, it would be decided whether the non-official historic titanium industry vision (based on a completed titanium metal value chain) should remain, or whether a new vision needs to be established. Chapter 4 will discuss methodology on how to collect information needed to compile the proposed roadmap.

3.5. The Conceptual Model

The conceptual model was constructed guided by the four keywords obtained from the research objectives. These keywords are roadmapping (in red), value chain (in blue), fragmentation (in green) and vision (in yellow). These keywords were first presented in Table 12 where the same colours were used to connect them to each of the research questions. The conceptual model is a graphic representation on how these research questions will be answered while simultaneously addressing the research objectives though the keywords. The colour coated conceptual model is displayed in Figure 13.

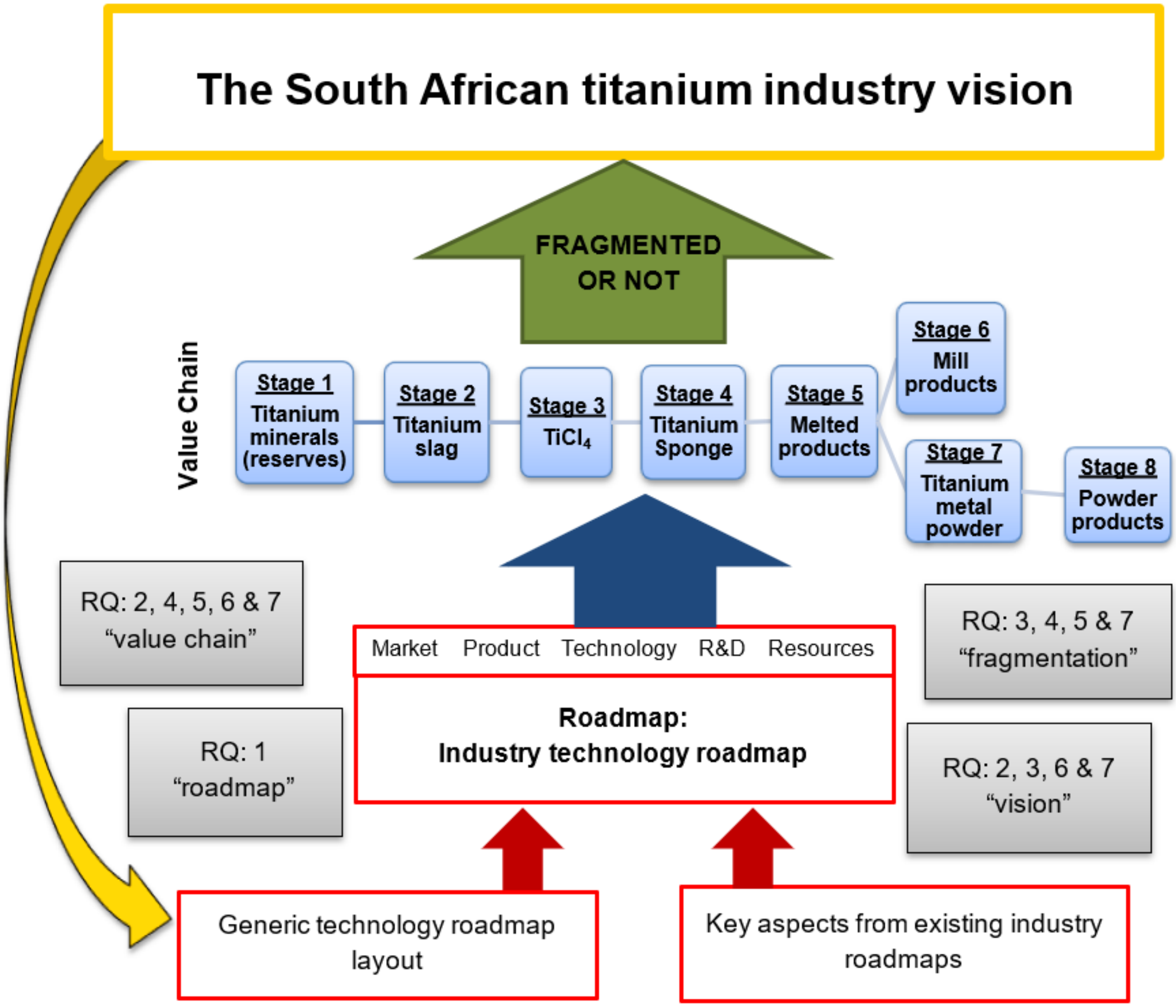


Figure 13. The conceptual model for this research.

The conceptual model was designed based on the four keywords that built on each other in order to reach the research objectives. From the bottom up, Figure 13 starts with the construction of a roadmap (in red). It is indicated that both a generic technology roadmap layout as well as key aspects from existing industry roadmaps was used to construct the industry technology roadmap structure used in this study. The roadmap layout considered five layers namely (market, product, technology, R&D and resources).

The next keyword addressed in the conceptual model was value chain (in blue). The titanium metal value chain was the centre of the research as roadmapping was done for each stage of the value chain, the completeness of the value chain determined the fragmentation and the vision elements of each stage of the value chain determined the overall industry vision. This can be observed in Figure 13 where the research questions were applied to the titanium metal value chain while considering the roadmap layout (yellow arrow going back down to roadmap).

The third keyword was fragmentation. It was expected that after applying the research questions to the local titanium metal value chain a decision could be made on whether the local titanium metal industry should remain fragmented or whether a complete value chain should be pursued.

The top section of the conceptual model was the overall titanium industry vision of South Africa (yellow). This vision was clear after following the steps presented in the conceptual model. By this time, a vision element for each of the value chain stages should have been compiled and could be used to generate the overall titanium industry vision. This vision was then be applied to the overall South African titanium metal industry roadmap.

3.6. Chapter Summary

The aim of Chapter 3 was to present the conceptual model used in this research. This framework aimed to provide guidance to the researcher in order to address all of the research questions. The conceptual model was constructed using four main keywords obtained from the research objectives to answer the research questions. These four keywords were roadmapping, value chain, fragmentation and vision. The chapter provides a context and explanation of each keyword.

The first keyword used in the design of the conceptual model was roadmap(ping). A brief review was provided on the selection of the industry technology roadmap as the selected roadmap type. The roadmapping approach followed in this study followed a prospective market-pull approach. The reasons for this was that this type of roadmap focuses on foresighting the development, commercialisation and deployment of new technologies. The roadmap looks from a current position towards the future while considering the desired end product that can be taken up by the market.

The roadmapping keywords were then applied to the roadmap design which was a combination of two main inputs. First the generic technology roadmap layout that was discussed in the literature survey. This layout has five proposed layers namely market, product, technology, R&D and resources. In this study each of these layers were approached by applying the three fundamental roadmapping questions: “Where are we now?”, “Where do we want to go?” and “How do we get there?” This was done over a 10 year timeline considering the medium-term (three years) and an additional seven years (long-term). The timeline started in 2021 and ended in 2030. The second main input for the roadmap design was obtained from the six industry technology roadmaps analysed in the literature survey section. Key aspects observed from these roadmaps were plotted on Table 9 in order to find relationships between the roadmap layouts. Table 9 indicates which of the roadmaps addressed the key points and which did not. A generalised roadmap layout from this industry technology roadmap key aspect analysis was used in conjunction with the generic technology roadmap to formalise the roadmap design used for this study.

The third keyword addressed in this chapter was fragmentation. The fragmentation of the South African titanium metal value chain was discussed, and a solution presented on how to roadmap this fragmented industry. The solution was to produce a roadmap for each stage of the titanium metal value chain by applying the generic technology roadmap layout (Figure 11) and that the key aspects collected from Table 9. The key aspects would only be applied to the overall South African titanium metal industry roadmap.

The next keyword used to construct the conceptual model was value chain. South Africa has a fragmented titanium metal value chain as the country has only four established stages namely stage 1 (mineral reserves), stage 2 (slag production), stage 6 (mill product production) and stage 8 (powder product production). This chapter also discussed what the South African involvement in all eight of the value chain stages were by indicating whether each stage's level was industry or R&D.

The last keyword to be addressed was vision. First a historic vision for the South African titanium metal industry was researched that indicated that the South African government has invested heavily in R&D to develop several stages of the titanium metal value chain. No official or published historic vision was obtained for the titanium metal industry. This indicated that a new vision was needed to obtain a fresh perspective on what he South African titanium metal industry should look like.

4. Chapter 4 Methodology and Research Design

4.1. Introduction

This chapter explains and elaborates on how the research was conducted. A systematic approach was followed with reference to accepted research best practices that would guide the outcome of this research to a logical conclusion. The outcomes of this research aimed to answer the research questions. A brief summary of the actions applied to answer the research questions is presented in Table 11.

Table 11. A summary of the research questions and the actions that would be taken to answer them.

	Research Question	Action for data collection
1	Which roadmap type should be applied to the South African titanium metal industry?	Desktop study: In the literature section different types of roadmaps were evaluated and the most suitable roadmap type selected, an industry technology roadmap.
2	What would the roadmap for the development of the South African titanium metal industry look like?	Expert interaction (during roadmapping) and roadmapping: Expert opinions regarding the South African titanium metal industry were collected through interviews and a survey. A roadmap was produced by constructing a vision from the collected data and the selected roadmapping model.
3	What should the South African titanium metal industry vision be?	Desktop study and expert interaction during roadmapping: Conducted a desktop study to determine if there was a historic vision for the titanium metal value chain. Expert opinions were obtained to formalise a 10 year vision element for each stage of the titanium metal value chain as well as an overall titanium metal industry vision.
4	What does the global titanium metal value chain look like?	Desktop study: Global titanium trends were investigated to establish who makes what and at what cost.
5	Which stage(s) of the titanium metal value chain is South Africa involved in?	Desktop study: Investigated what industry and R&D have been doing within the local titanium industry.
6	Which stage of the titanium metal value chain should South Africa focus on?	Expert interaction during roadmapping: Expert opinions were obtained along each stage of the titanium metal value chain.
7	a) Should South Africa be active in the full titanium metal value chain? OR b) Should the South African titanium industry value chain remain fragmented?	Expert interaction during roadmapping: This was answered by analysing all of the feedback obtained through interviews as well as a survey. The global titanium industry was also considered.

In addition to elaborating on the methodology used to conduct this research, Chapter 4 will introduce a conceptual model of how the objectives will be reached by answering the research questions. Four research objectives were presented in Section 1.3 and from each objective a keyword was selected as concepts and ideas to build the conceptual model. The four keywords from the four research objectives are roadmapping, value chain, fragmentation and vision. Table 12, showcases how each keyword is related to a research question. There is a direct link between the use of colours in Table 12 and the conceptual model as illustrated in Figure 13.

Table 12. The link between the identified research objective keywords and the research questions.

Research Question	Roadmapping (red)	Value Chain (blue)	Fragmentation (green)	Vision (yellow)
Flow on the conceptual model				
1. Which roadmap type should be applied to the South African titanium metal industry?	X			
2. What would the roadmap for the development of the South African titanium metal industry look like?	X	X		X
3. What should the South African titanium metal industry vision be?	X		X	X
4. What does the global titanium metal value chain look like?		X	X	
5. Which stage(s) of the titanium metal value chain is South Africa involved in?		X	X	
6. Which stage of the titanium metal value chain should South Africa focus on?	X	X		X
7. a) Should South Africa be active in the full titanium metal value chain? OR b) Should the South African titanium industry value chain remain fragmented?	X	X	X	X

Although the end goal of this research was to produce a roadmap for the South African titanium metal industry, this concept can also be seen as a starting point. In order to produce a suitable roadmap, the roadmapping type should be identified from the start with inputs from industry and existing roadmapping models. The roadmap structure was applied to the identified South African titanium metal value chain that could either be complete or fragmented. The results section aimed to determine the fragmentation status while identifying the vision element for each stage of the local titanium metal industry. This vision elements then became the drive to develop a roadmap for each stage of the titanium metal value chain.

As outlined in Table 11, three main actions were applied to answer the research questions. These actions were based on methods of data collection namely a desktop study, expert interaction and roadmapping.

4.2. Desktop Study (Secondary Data)

The purpose of the desktop study was to (from Table 11):

- select the best suited type of roadmap for the South African titanium metal industry,
- find out whether there was a historic vision for the South African titanium industry,
- investigate the local titanium metal scene to find out what research institutions and industry have been doing locally, and
- investigate global titanium market.

Secondary data was a valuable source of information. Secondary data is data that was initially collected for other purposes and consists of both raw data and published summaries (Saunders, Lewis and Thornhill, 2016). This type of data includes minutes of meetings, reports, newspapers, company websites as well as other data published in scholarly journals and revealed in literature searches. Secondary data used in this research was obtained through a desktop study.

Secondary data can be interpreted both quantitatively and qualitatively. Secondary data could be difficult to obtain. This is because some sources tend to keep their information private or ask a fee to access it. It is therefore important to identify the data required and ascertain whether the needed data is available and accessible.

4.3. Expert Interaction (Primary Data)

One of the key components needed to create a representative roadmap is the inclusion of opinions from industry experts. Two forms of industry expert interactions were used to collect data for this research during roadmapping. The first was interviews conducted with 37 local industry experts and the second was an online survey with 17 selected industry experts with a 94 % response.

According to Table 11, expert interactions was needed to:

- establish the South African titanium industry vision,
- develop a roadmap for the South African titanium industry (driven by the vision),
- identify the stage(s) of the titanium metal value chain South Africa should focus on, and
- indicate whether South Africa should develop a full titanium metal value chain or whether the South African titanium industry should remain operating on a fragmented value chain.

Expert interactions followed a systematic sequence. Firstly, interviews were held with selected individuals involved in different stages one the titanium industry value chain. These interviews introduced the experts to the research problem statement. Depending on the specific stage of the value chain the individual is involved in, the interviewee's view on the industry outlook for the value chain was discussed. These discussions covered the potential markets, products, technologies, R&D, resources as well as socio-economics.

The second stage of expert interactions built on the information collected from the interview process. This was done in the form of an online survey with the main aim to establish the vision elements for each of the stages involved in the South African titanium metal value chain. A survey questionnaire was sent to leading industry experts to validate each of the vision elements as well as the complete South African titanium metal industry vision.

4.3.1. Interviews

Research interviews are defined by Saunders, Lewis and Thornhill (page 388, 2016) as: "purposeful conversation between two or more people, requiring the interviewer to establish rapport and ask concise and unambiguous questions, to which the interviewee is willing to respond, and listen attentively". Interviews were conducted for this research with the purpose to gather valid and reliable data that was relevant to the research questions and objectives.

4.3.1.1. Semi-structured Interviews

The main interview method selected for this study was a semi-structured interview method. This method was selected based on the nature of the research being exploratory as well as evaluative.

The purpose of an exploratory study is to ask questions about what is happening in the topic of interest. This was done through, the research questions asking what is happening in the titanium industry, in the titanium value chain and in roadmapping. An exploratory study aids in understanding a specific issue, problem or phenomenon (Saunders, Lewis and Thornhill, 2016). An evaluative study aims to figure out how well something works. This study is used to measure the effectiveness of an organisation's business strategy, policy, programme, initiative and process (Saunders, Lewis and Thornhill, 2016). In relation to this study the question has been asked on how the global fragmented titanium value chain works and how South Africa could successfully apply this to its titanium metal value chain. The selected interview types for this research was semi-structured interviews. Semi-structured interviews would provide an important background on contextual material (e.g. the titanium market) and would provide insight on the relationship between the evaluation or effectiveness criteria (e.g. the value chain).

When conducting semi-structured interviews, the researcher has a pre-prepared list of themes and key questions to be covered. All of the questions might not be suitable for every interview, so the interviewer can select the appropriate questions during the interview (Saunders, Lewis and Thornhill, 2016). With semi-structured interviews, the interviewer is also allowed to add relevant questions to the list when deemed needed. The flow of the questions can also be adapted and changed depending on the flow of the interview. Data collected during the interview was captured by audio-recordings of the conversation as well as by note taking. Interviewees were aware of the recording and had the option to say no to the recording.

4.3.1.2. Pilot Interviews

Pilot interviews are held with people prior to finalising the interview pattern to be followed during the semi-structured interviews. For this research, pilot interviews were held with students from the author's research group. These interviews were only used on pilot bases and the answers were not included in the results.

4.3.1.3. Sampling Selection

Probability sampling is a compromise between accuracy and the amount of time and money invested in data collection, analysing and checking (Saunders, Lewis and Thornhill, 2016). This type of sampling is common within PhD dissertations as money and time are limited. One of the most important considerations for probability sampling is that the sample has to be representative of the sample population (Saunders, Lewis and Thornhill, 2016).

The selected sampling technique for the study was purposive. With this sampling technique one selects the cases that will aid to answer your research questions and meet your objectives (Saunders, Lewis and Thornhill, 2016). This type of sampling is not considered to be statistically representative of the target population (the titanium industry), the reason being that the individuals to be interviewed forms part of a small community of experts along the titanium value chain. The selected experts must have experience in at least one stage of the titanium metal value chain and must have sufficient knowledge of the complete titanium value chain that could contribute towards the roadmap for the South African titanium industry. When using this type of sampling the control over the sample contents is specified according to the selection criteria (Saunders, Lewis and Thornhill, 2016).

Individuals selected for expert interaction were considered key members of the South African titanium industry. As this industry is still developing in South Africa, this included industry experts and established researchers. A total of 37 experts were interviewed. Interviewees were selected from 13 different companies. These companies and their representation are displayed in Figure 14. Approximately 30 % of the interviewees were from industry and 70 % from R&D.

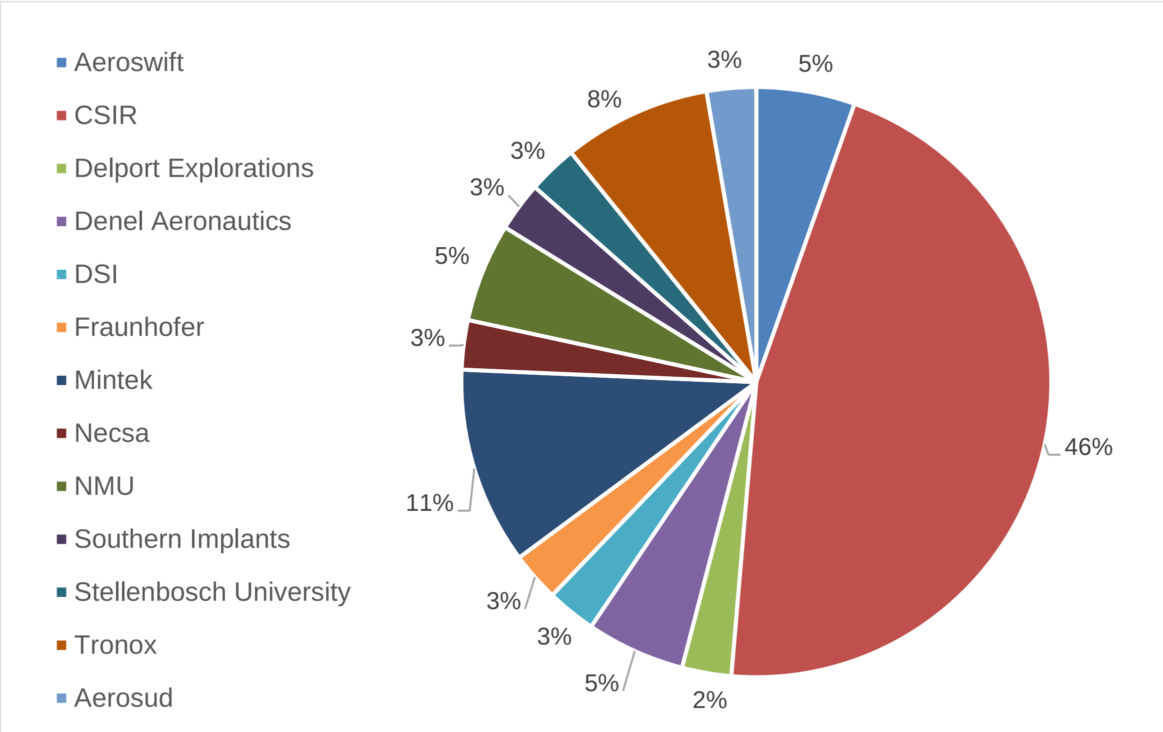


Figure 14. A list of companies involved and their representation.

Interviewees were asked to indicate their primary, secondary and tertiary focus within the titanium metal value chain. The distribution of interviewees involved in each of the eight stages of the titanium metal value chain is indicated in Figure 15.

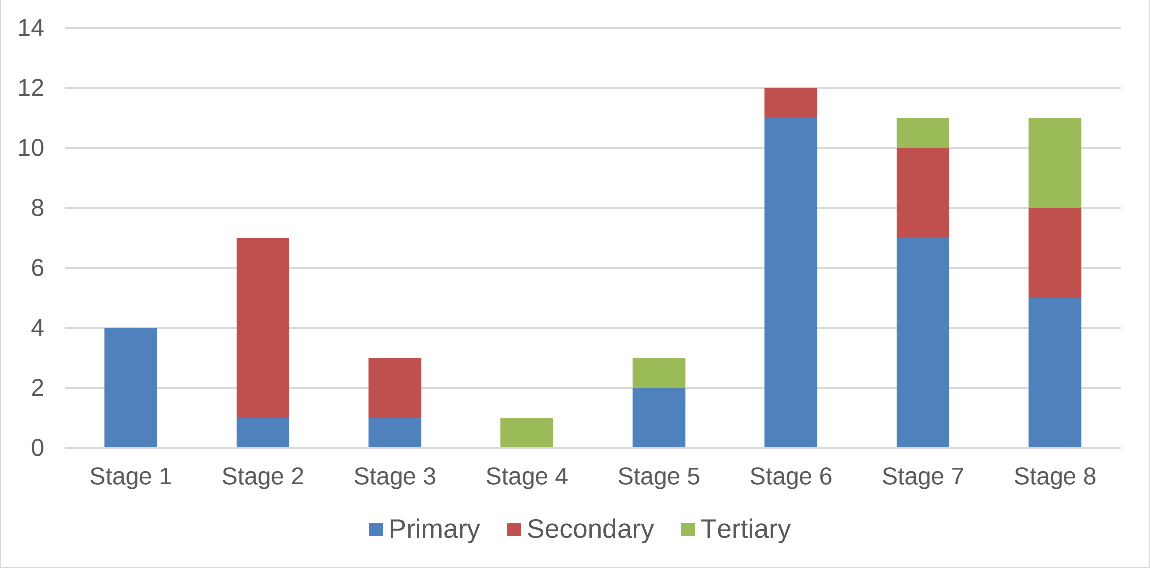


Figure 15. Distribution of primary, secondary and tertiary focus of interviewees along titanium metal value chain.

From Figure 15, the bulk of the interviewees were from the downstream end of the titanium metal value chain (stage 6 - 8). More than three interviewees were interviewed for all the stages except for stage 4 (titanium sponge production). South Africa is not producing titanium sponge and limited research has been conducted locally on this stage of the value chain.

It was important to note that in South Africa, only four of the eight identified stages of the titanium product value chain are operated (functioning) on industry level. Industry experts are individuals with expertise within the titanium industry. Their participation is defined by the area of experience (De Cavin, 2012). In South Africa, industry experts could be obtained from the four stages operating on industry level. These are titanium reserves (stage 1), titanium slag (stage 2), titanium mill products (stage 6) and titanium powder products (stage 8). Information collected from the interview process was used to identify suitable markets and products for the South African titanium metal industry as well as working backwards from the product to determine the value chain.

In contrast with the fragmented nature of the titanium industry value chain of South Africa, research has been conducted locally on the full titanium metal value chain. Researchers within a selected field study a specific topic carefully in order to discover new information or to understand existing information better. With the drive from the South African government to develop a South African titanium industry, dedicated funding has been allocated towards titanium research. This is important when considering sample selection as Saunders *et al*. (2016) state that your sample selection should represent the target population and therefore the larger portion of researchers compared to industry experts are feasible.

4.3.1.4. Interview Layout

Before each interview, the interviewee received an information sheet with relevant information to prepare for the interview (see Appendix A: Interviewee Information Flyer). According to Saunders *et al*. (2016) an information sheet promoted validity and reliability as the information informed the interviewee on the type of information intended to be collect and he/she would therefore be more prepared.

The interviews were designed to take no more than 30 minutes. The interviews followed a semi-structured approach, meaning that additional questions could be added if the conversation permitted it. The template used for the interviews is available in Appendix B. The Interview Template Questions which were not applicable to a certain interviewee were excluded from the conversation, if needed (if not involved in a certain value chain stage). A brief layout of the interview structure is presented below. The complete interview guide (including the questions) is available in Appendix C: Interview Question Guide.

A. The interview started with a brief introduction of the interviewer followed by his/her background and the background of his/her research.
B. A short discussion was held on the interviewee's understanding on the information received prior to the interview.
C. The interviewer then proceeded to explain/discuss the titanium product value chain:
    - the global value chain,
    - where South Africa fits into the value chain,
    - beneficiation would be discussed,
    - fragmentation within the titanium value chain will be discussed, and
    - specific reference was made to the relevant stage of the value chain the interviewee was involved in.

QUESTIONS FOCUSING ON INTERVIEWEE'S REFERENCE FRAMEWORK

1. "What is the current position of your stage of the value chain and what development and improvements do you expect in the future"
2. "Who is your supplier and who is your market?"

QUESTIONS FOCUSING ON THE SOUTH AFRICAN TITANIUM INDUSTRY

3. "What do you consider the preferred marked is for South Africa within the titanium metal industry?"
4. "Based on your knowledge of the South African titanium metal industry, should we keep doing what we are doing (part of fragmented value chain), or should we try to develop the complete titanium metal value chain?"
5. "Why is it important for you that South Africa follows the value chain route you suggested? "
6. "Market-pull or technology-push approach? Or both?"
7. "Where do you see the major developments within the South African titanium metal industry within the next three years?"
8. "Where do you see the major developments within the South African titanium metal industry within the next 10 years?"
9. "What stage of the titanium metal value chain do you feel has the most disruption potential?"

4.3.2. Survey

The survey was the second form of expert interaction. The main aim of the survey was to confirm the vision elements for each stage of the South African titanium metal industry that was identified during the interviews (top-down approach). These new verified vision elements were then used to drive the titanium metal industry roadmaps for each stage of the value chain. Upon completion of the interviews, the data collected was processed in order to produce a rough draft of the current South African titanium industry landscape as well as a South African industry outlook. This information covered the "Where is South Africa now?" and "Where does South Africa want to go?" questions that formed an essential part of the roadmapping process.

4.3.2.1. Sample Selection for the Surveys

During the interviews, experts were asked which stage of the value chain they consider themselves experts in. The sample selection for the survey was done by selecting two experts from each stage of the titanium metal value chain. Titanium mineral reserves and upgraded titanium slag production (stage 1 and 2) had the same experts and only two experts were selected to represent both stages during the survey. Based on the mentioned sample selection 14 experts were selected. Three additional experts were also included as they had an overall understanding of the titanium industry and especially the techno-economics of this industry. The total amount of experts who received the electronic survey were 17 of which seven were from industry and ten from R&D.

4.3.2.2. Survey Responses

The survey was designed using KwikSurvey and can be viewed in Appendix D: The Survey Design. The survey was sent out to 17 experts and 16 responded (94 % response rate). To confirm that the survey covered all of the identified titanium metal value chain stages each expert had to indicate which stage of the value chain he/she felt comfortable commenting on. The results are displayed in Figure 16.

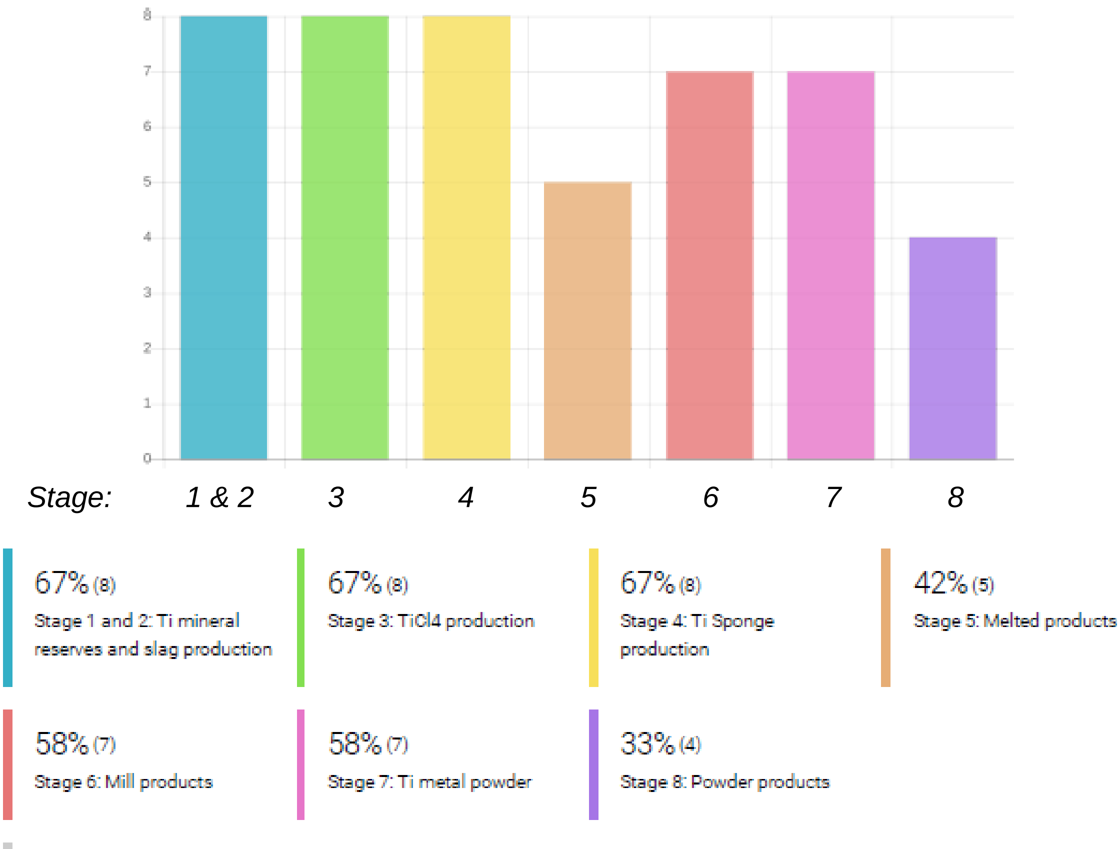


Figure 16. Titanium metal value chain representation of experts that undertook the survey.

Figure 16 is an indication of the titanium metal value chain stage(s) each of the experts felt comfortable in commenting on. The distribution over the eight value chain stages is good. The bulk of the experts indicated that they have experience and understanding of titanium mineral reserves and slag production, $TiCl_4$ production, mill product production and titanium metal powder production. The least number of experts had knowledge in the production of products from titanium metal powder and the production of titanium melted products.

4.4. Roadmapping

The last and final action to answer the research questions was the creation of an industry technology roadmap. The art of producing this roadmap is referred to as roadmapping.

4.4.1. Roadmap Design

All the information collected up to this point was used as input to create an overall roadmap for the South African titanium metal industry. The proposed roadmapping model was presented in the conceptual model, Section 3.1. According to this model each stage of the titanium metal value chain should first be addressed separately. This should be done by applying the generic roadmapping model to each stage the fragmented titanium metal value chain (see Figure 11). The roadmap design for each stage of the value chain should follow the generic technology layout and discuss market, product, technology, R&D as well as resources each in their own layer. The three roadmapping questions should be applied to each stage of the value chain to determine, for that stage, “Where is South Africa now”, “Where does South Africa want to go?” and “How will South Africa get there?”. Each roadmap should display the five layers over a three and additional seven year timeframe. Each roadmap should also be constructed considering the key aspects identified by analysing actual industry technology roadmaps (Chapter 2, Section 2.1.6 and Chapter 3, Table 9 in Section3.1.2).

From the roadmaps produced for the individual value chain stages, the “Where does South Africa want to go?” question refers to the vision element for that stage. All of the value chain stage vision elements should then be combined to produce one overall South African titanium metal industry vision (bottom-up approach). This vision should then drive the South African titanium metal industry roadmap. This roadmap should be displayed using a temporal approach. This roadmap should be elaborated on following the key aspects identified though analysing actual industry technology roadmaps. The most abundant key aspects used to produce these industry technology roadmaps are summarised in Table 13. In Table 13 “Yes” indicates that this roadmap would cover the key aspect and “No” indicates that the selected key aspect would not be covered by this roadmap. Inclusion and exclusion were determined based on popular usage of the key aspects in the working roadmaps as well as applicability to the titanium industry.

Table 13. Key aspects selection to include or exclude certain topics when developing the South African titanium metal industry roadmap.

	Topic discussed	A roadmap for the South African titanium metal industry
1	Timeframe	2021-2030
2	Analysis type	Market-pull
3	Discuss Phase 1: Planning & preparation	Yes
4	Discuss Phase 2: Visioning	Yes
5	Discuss Phase 3: Roadmap development	Yes
6	Discuss Phase 4: Roadmap implementation, monitoring and revision	No
7	Build on previous Roadmap(s)	No
8	Workshops were held	No
9	Discussed the current situation	Yes
10	Cover global sector	Yes
11	Cover global markets	Yes
12	Sufficient graphics and illustrations	Yes
13	Prioritisation or rating processes	Yes
14	Established R&D structure already exist in country	Yes
15	Mention energy consumption	Yes
16	Discuss sustainability & socio-economics	Yes

The reason for excluding three topics in Table 13 was because this research forming part of a PhD thesis and therefore some limitations applied as discussed in the limitation section (Section 4.6). This applies for point numbers 6, 7 and 8.

4.4.2. Building the Roadmap

The roadmap development path (visualised in red on the conceptual model, Figure 13) was based on combining the generic technology roadmap structure with the key aspects identified from industry roadmaps. All of the key aspects identified were first presented in Table 9 (Chapter 3, Section 3.1.2) and the selected aspects indicated on Table 13 with “Yes”. The selected aspects from Table 13 were used as a guide to construct the individual roadmaps as well as for a layout guide to elaborate on the overall South African titanium metal industry roadmap (Chapter 13).

The layout followed by the overall South African titanium metal industry roadmap project was based on the four phases identified by the key aspects namely: planning and preparation (Phase 1), visioning (Phase 2), roadmap development (Phase 3) and roadmap finalisation (Phase 4). For the purpose of this study, the usual Phase 4 in roadmaps which includes roadmap implementation, monitoring and revision, was beyond the scope of this study and was replaced with roadmap finalisation. The different phases of roadmaps related to this study are displayed in Figure 17.

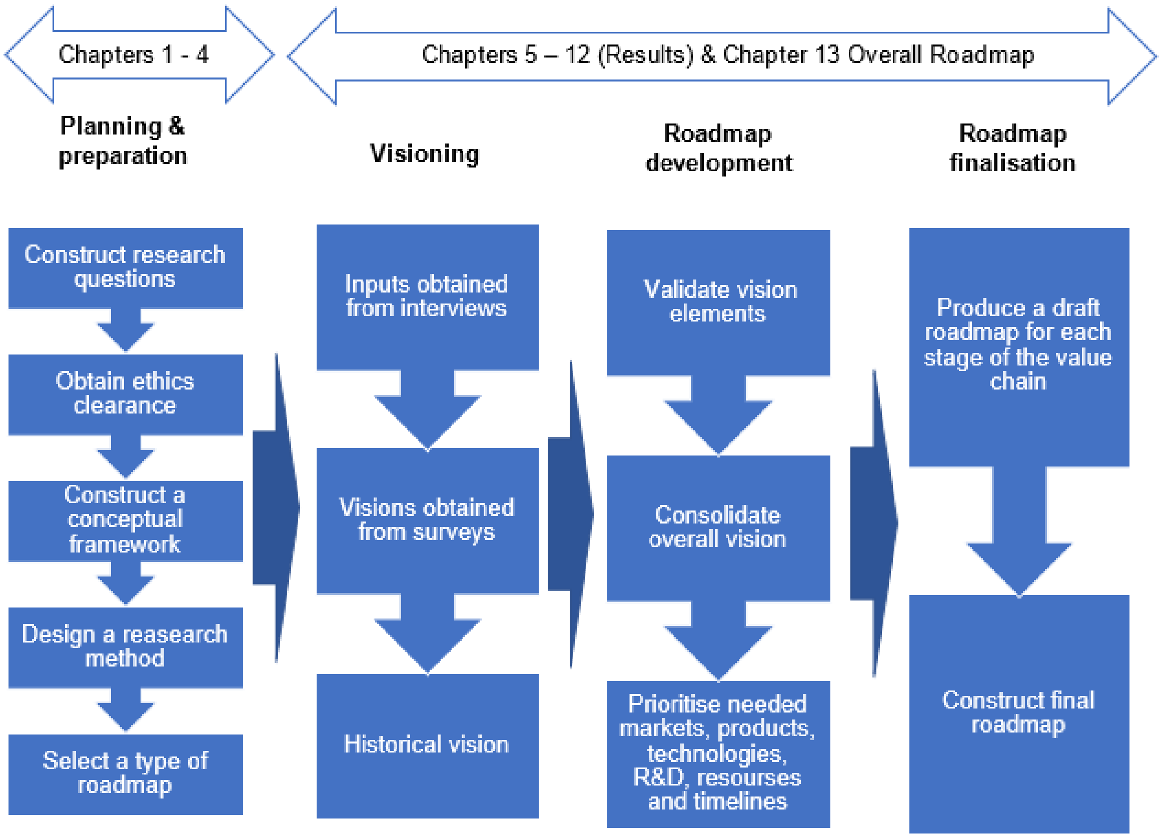


Figure 17. Roadmap development path.

The roadmap development path displayed in Figure 17 is similar to the path followed by Londo *et al.* (2013) and it is the preferred development path followed by the majority of the industry roadmaps analysed for this study. The planning and preparation portion of Figure 17 does not form part of the results section of this research and has been addressed in Chapter 1 - 4. The visioning, roadmap development path as well the roadmap finalisation phases form part of Chapters 5 to 13. The results chapters focus on the stages of the value chain and each stage was discussed according to the generic roadmapping layout which is market, products, technology, R&D and resources (subsections in the results chapters).

The layouts of Chapters 5 to 11 all follow a similar trend with minor exceptions:

- For example, stage 1 and stage 2 of the titanium metal value chain (mining and upgrading of titanium concentrates) were discussed in one chapter (Chapter 5) as both stages are controlled by the same mining and upgrading facility, as well as company. This resulted in the identification of only one combined vision element for the two stages and hence one combined roadmap.
- The subsection termed “Resources” in Chapters 5 to 11 includes (i) the availability of raw materials or feedstock required for each stage, (ii) human capital development, and (iii) the third resource electricity will only be

discussed once in Chapter 5 as the concept remains the same for all of the result chapters.

- Chapter 12 is on titanium scrap and ferrotitanium. This chapter was added for the sake of completion, but the roadmapping structure was not applied as this stage was excluded from the titanium metal value chain used in this study (see limitation Section 4.6).

Each stage of the titanium metal value chain will be discussed separately in Chapters 5 to 11. Based on the fragmented nature of this value chain it was decided to construct a separate roadmap for each of the value chain stages. The roadmap type for each stage remained an industry technology roadmap and the complexity would follow Type 1 temporal layout with time-based layers. The full-time span would cover a 10 year period 2021 to 2030. A template of the proposed roadmap layout for the individual stages of the titanium metal value chain is displayed in Figure 18.

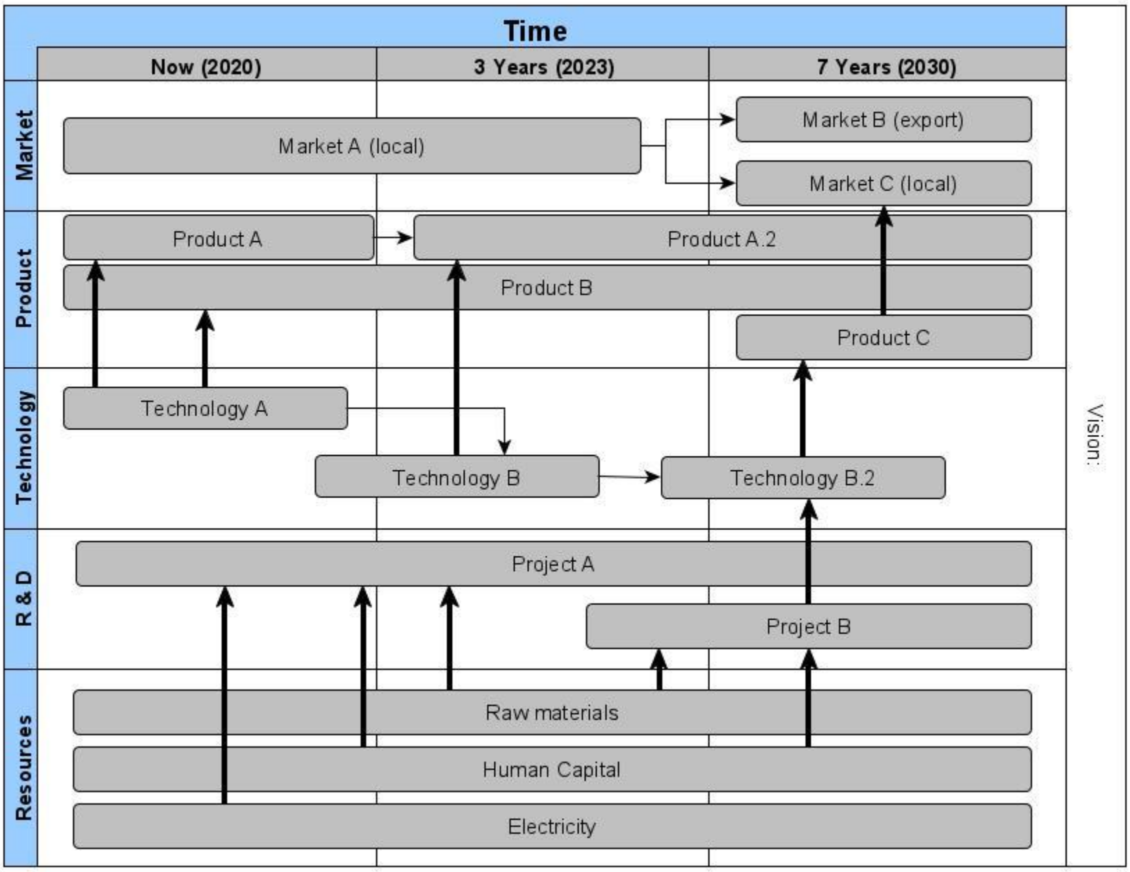


Figure 18. Template for roadmap layout for each stage of the titanium metal value chain.

From the template presented in Figure 18 it is observed that the different roadmapping layers can interact with each other. This is presented by arrows indicating what themes (blocks within each layer) or layers are linked. Thick arrows indicate interaction between different layers and thin arrows interaction between themes within the same layer. The arrows indicate a dependence of themes and layers as the next theme can only be started once the prior theme has been achieved. As with the generic roadmapping layout the themes will adhere to time on the roadmap's x-axis and systematically progress to the overall vision displayed on the right-hand side of the roadmap.

4.5. Ethical Considerations

The University of Pretoria requires ethics approval for all research that include the collection of personal or sensitive data where humans or animals are involved. Approval for this research was obtained from the EBIT Faculty Committee for Research Ethics & Integrity, Reference number EBIT/101/2019.

Ethics clearance was required to ensure that interaction with internal and external candidates were conducted in a professional and ethical manner to protect the image of the University and the student. Ethics clearance was required the expert interactions. The participation of each expert was voluntary, and permission was asked before conducting the research (written approval). The identities of the interviewees as well as their inputs to the study were kept anonymous. No potential detrimental environmental impact occurred, or hazardous materials were used during the project.

4.6. Limitations to applying the methodology

4.6.1. Limitations to the value chain:

- This research is limited to titanium metal and titanium pigment (TiO_2) will only be discussed in context where its production directly affects the production of titanium metal. Although these two end products share the first three stages of the identified titanium value chain, the processes, required technologies and expertise differ significantly. It was therefore decided to focus solely on the titanium metal value chain and pigment would only be mentioned in circumstances where this industry has/had a direct influence on the production of titanium metal.
- The author is aware that titanium recycling forms a large part of the global titanium industry. It has, however, been decided to limit the focus on scrap and ferrotitanium in this study. Chapter 12 addresses this. This limitation was applied as including scrap and ferrotitanium to a larger extent would have added to the complexity of the study. South Africa has not yet established a sophisticated titanium metal recycling industry. The reasons for this include the small quantity of titanium available for recycling as the aerospace mill product stage of the titanium metal value chain is not developed locally. The

author is aware of the importing of titanium scrap for alloying purposes within the stainless steel industry, which is the largest reported activity on titanium scrap. A Master's Thesis produced in 2016 by Stellenbosch University addressed this in detail (Durr, 2016).

4.6.2. Limitations to data collection:

- The data used in this study was obtained from secondary sources as well as from expert sources. As far as the author of this study is aware the data used is accurate and has been validated though secondary data (e.g. Roskill Reports) where possible. The author does not take any liability for the data obtained from industry experts.
- Market research is not readily available online and market reports are expensive. Three main reports were used in this study two Roskill reports on titanium (2013 and 2019) as well as one report by QY Research Group (2016) on titanium metal powder specifically. No later version of the titanium metal powder market was purchased, and the 2016 version was used as the main source of market information on titanium powder. Local import and export data on downstream titanium products are not readily available which could result from the fact that applications are mainly in the military and defence industries.

4.7. Chapter Summary

Chapter 4 addressed the methodology followed in the research. This chapter explains the processes and steps required by the researcher to complete the study and thereby answer the research questions linked to the research objectives. The chapter discussed how data was collected using both secondary and primary data sources. The chapter also elaborated on the methodology used to construct the roadmaps produced from the collected data. Lastly ethical considerations and study limitations were discussed.

The first proposed method for data collection was a desktop study to collect secondary data. This data was collected to ensure the correct roadmap type was selected, to determine if there was a historic vision for the local titanium metal industry, investigate what R&D is currently conducted and investigate the global titanium market.

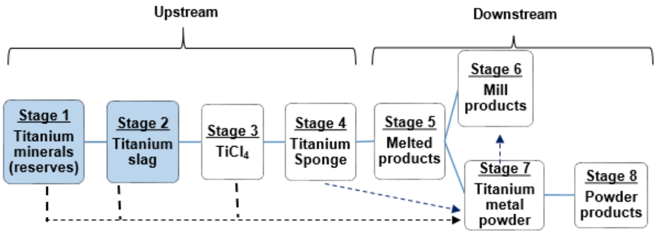
Primary data was obtained through expert interactions. The methodology presented in Chapter 4 indicated a two phase expert interaction. The first was interviews conducted with both industry and R&D experts and the second a follow up survey with selected experts that were interviewed. The aims of the interviews were to determine the South African titanium industry vision (vision elements for each stage of the value chain as well as the overall vision), to collect information needed to construct roadmaps for the study, to identify which stages of the value chain South Africa should focus on and determine whether South Africa should have a complete or fragmented titanium metal value chain. The main aim of the survey was to confirm the vision elements obtained from the interviews.

Next the methodology used for roadmap construction was discussed. The methodology indicated that roadmaps for each stage of the titanium metal value chain should be produced as well as one overall roadmap for the South African titanium metal industry.

Roadmaps constructed for each stage of the titanium metal value chain should followed the generic technology roadmapping layout and consider market, product, technology, R&D as well as resources, each in their own layer. The three roadmapping questions should be applied to each stage of the value chain to determine, for that stage, “Where is South Africa now”, “Where does South Africa want to go?” and “How will South Africa get there?”. This should be done for a 10 year period (2021 – 2030). Each of the value chain stage roadmaps should be constructed according to the key aspects identified through industry technology roadmaps. A roadmap template was presented in the methodology section that indicated how the individual roadmaps should be constructed.

The overall South African titanium metal industry vision should be obtained by combining all of the vision elements from the individual value chain stages. This vision should be used to construct the overall South African titanium metal industry roadmap which followed a metamorphic roadmap design rather than a temporal design used by the individual roadmaps. The key aspects identified though industry technology roadmaps should be used to elaborate on the metamorphic roadmap design.

5. Chapter 5: Stage 1 & 2 (Titanium Reserves and Slag)



5.1. Literature Review

The literature review on the first two stages of the titanium value chain will be discussed together in Chapter 5. Countries that have economic titanium reserves would often mine and upgrade minerals locally before exporting or processing the slag further. Both stages are also managed by the same company. This is also the case for South Africa and therefore the first two stages of the value chain will be discussed in the same chapter.

5.1.1. Titanium Minerals

Titanium is the ninth most abundant element in the earth's crust and can be found in most rocks (Woodruff and Bedinger, 2013). Titanium occurs naturally in several minerals, but only two minerals are considered as economic feedstock for titanium metal or pigment production. These minerals are rutile and ilmenite. Pure natural rutile consists mostly of TiO_2 (94 - 96 %) with minor quantities of iron (Dooley, 1975). Rutile has a polymorph, namely anatase, which has the same chemical composition, but a different crystal structure (Woodruff and Bedinger, 2013). Ilmenite consists of larger quantities of iron and the general formula is $FeO{\cdot}TiO_2$. Depending on the ferric and ferrous ion concentrations, TiO_2 comprises 40-60 % of ilmenite (Dooley, 1975). The lower concentration of TiO_2 indicates that ilmenite contains greater quantities of contaminants compared to rutile. Except for iron, other common impurities are zirconium, chromium, aluminium, magnesium, manganese, niobium and silicon.

Titanium occurs in primary magmatic and secondary placer deposits. Ilmenite crystallises out of magma at high temperatures to form magmatic ilmenite. Only two economically feasible magmatic ilmenite deposits are mined at the Lac Tio mine in Quebec, Canada and at Tellnes in southern Norway (Woodruff and Bedinger, 2013). More than half of the global titanium production is obtained from secondary placer deposits. These deposits are formed from weathered magmatic or metamorphic parent rock. This weathered material is then transported, sorted and deposited on shorelines or dune settings. By the time the minerals reach the shoreline only the relevantly resistant minerals remain in high concentrations. The bulk of the rutile being mined is as a sand, known as heavy mineral sand deposits (has a specific gravity >2.85 g/cm^2) (Woodruff and Bedinger, 2013). Ilmenite is commonly found in both placer and magmatic deposits. Ilmenite rocks include ilmenite-magnetite or ilmenite-haematite. Heavy mineral sand deposits are preferred above hard-rock mining as this is a cheaper procedure (Dooley, 1975).

Most of the economic titanium reserves are ilmenite, but the preferred mineral, especially to the pigment industry, which is ±90 % of the titanium industry, is rutile. This is due to rutile having a very high index of refraction and a lower contaminant, especially iron, content (Woodruff and Bedinger, 2013). There is a difference in quality for global ilmenite minerals as well as between deposits within the same country (Bordbar, Yousefi and Abedini, 2017; Dooley, 1975). This is due to the different types of deposits being mined as well as the different source rock composition when considering placer deposits.

5.1.2. Upgraded Titanium or Titanium Slag

To upgrade titanium minerals (especially ilmenite) means to increase its purity (concentration of titanium) by removing contaminants. Based on the mineralogical differences of rutile and ilmenite the ores are generally treated/upgraded separately. The beneficiation of both ore types follow conventional beneficiation techniques and the general flow path is indicated in Figure 19.

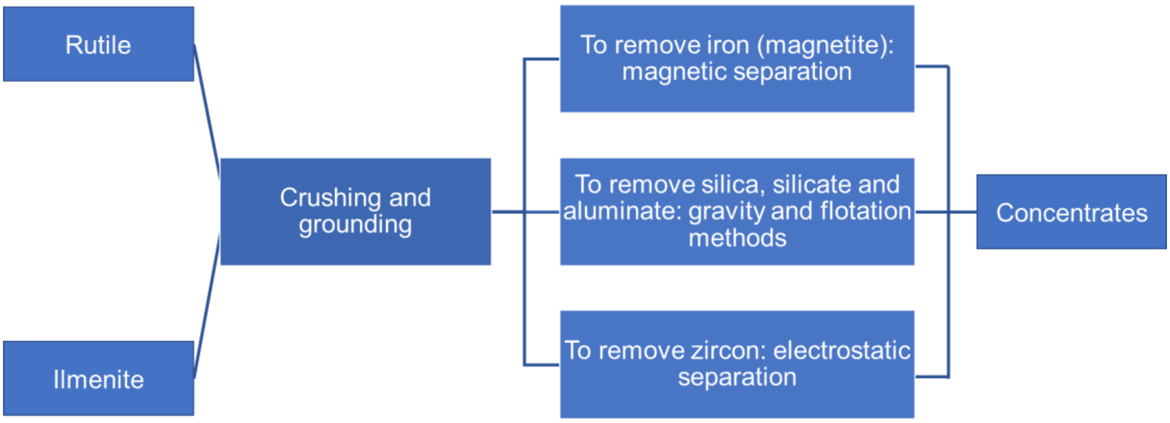


Figure 19. The basic beneficiation steps for rutile and ilmenite ores. (Source: Bordbar, Yousefi and Abedini, 2017).

After beneficiation of the rutile and ilmenite ores the TiO_2 is more concentrated and high-grade TiO_2 is obtained. These concentrates can then be further processed depending on the end product that is required (Bordbar, Yousefi and Abedini, 2017). Rutile, the purer titanium mineral, can either be natural or synthetic. Synthetic rutile is produced by upgrading ilmenite and has a TiO_2 percentage of 92 – 95 %.

When the ore mineral is ilmenite the beneficiation steps are slightly more complex to the beneficiation steps of rutile as the ore contains more contaminants. The aim of ilmenite beneficiation is to produce one of two products namely synthetic rutile (TiO_2 = 92 - 95 %) or titanium rich slags (TiO_2 = 80 - 90 %). After obtaining ilmenite concentrates (see Figure 19) the product can be upgraded by removing impurities via chemical processes (Bordbar, Yousefi and Abedini, 2017). Chemical attack is especially needed to remove iron from TiO_2. Except for iron, chromium and vanadium are also removed in order to upgrade the ore. From these processes, the two upgraded products are titanium rich slag and synthetic rutile.

5.2. Global Outlook: Titanium Mineral Reserves and Slag

On a global scale the titanium ore market can be divided into five regions namely Asia Pacific, North America, Europe, Latin America and the Middle East & Africa (Sawant, 2018). From these, Asia Pacific is the global market leader (Sawant, 2018). As mentioned, the ore is divided into ilmenite and rutile reserves. Not all countries that mine ore, process the ore into titanium sponge, South Africa being the key example exporting rutile and upgraded titanium slag (Roskill reports, 2013) Table 14 displays the countries that hold and mine titanium reserves.

Table 14. Rutile and ilmenite reserves as well as mined production in alphabetical order as per country (Source: USGS, 2018, 2019).

Country	Mineral	Reserves (Mt)	Mined Production			
			2016 (Mt)	2017 (Mt)	2018 (Mt)	2019 (Mt)
Australia	Ilmenite	250 000	780	900	720	660
	Rutile	29 000	380	450	141	140
Brazil	Ilmenite	43 000	48	50	66	70
	Rutile	-	-	-	-	-
Canada	Ilmenite	31 000	595	475	630	690
	Rutile	-	-	-	-	-
China	Ilmenite	220 000	840	800	2 100	2 100
	Rutile	-	-	-	-	-
India	Ilmenite	85 000	180	200	319	320
	Rutile	7 400	19	20	15	14
Kenya	Ilmenite	850	280	375	272	200
	Rutile	380	84	80	90	74
Madagascar	Ilmenite	8 600	92	140	228	300
	Rutile	-	-	-	-	-
Mozambique	Ilmenite	14 000	540	550	575	590
	Rutile	880	7	7	8	8
Norway	Ilmenite	37 000	260	260	236	260
	Rutile	-	-	-	-	-
Senegal	Ilmenite	NA	250	300	297	290
	Rutile	NA	9	10	9	9
Sierra Leone	Ilmenite	-	-	-	-	-
	Rutile	490	130	160	114	120
South Africa	Ilmenite	35 000	1 020	1 300	765	820
	Rutile	6 100	67	65	103	110
Ukraine	Ilmenite	5 900	210	350	373	380
	Rutile	2 500	95	90	94	94
USA	Ilmenite Rutile	2 000	100	100	100	100
Vietnam	Ilmenite	1 600	240	300	105	150
	Rutile	-	-	-	-	-
Other countries	Ilmenite	26 000	71	90	83	60
	Rutile	400	8	15	21	29
Totals	Ilmenite	870 000	5 500	6 200	6 870	7 000
	Rutile	62 000	800	900	594	600
	World total (ilmenite and rutile)	932 000	6 300	7 100	7 460	7 600

As explained in the literature review section, titanium is mainly obtained from heavy mineral sand deposits and these sands produce several product streams. Although the deposits are predominantly ilmenite the concentration of the other minerals shapes the revenue as these minerals contribute to cover the cost of mining (ILUKA, 2019). Titanium feedstocks are generally sold as raw materials (ilmenite and rutile) or as upgraded feedstocks (synthetic rutile and slag). Chloride ilmenite is an ilmenite feedstock with a TiO_2 content between 58 % and 65 % while sulphide ilmenite has a TiO_2 content of 45 % to 58 % .Trade contracts of raw and upgraded titanium materials are normally long-term that resulted in extended periods indicating price stability and modest price growth (ILUKA, 2019). Figure 20 displays the annual mineral sands prices.

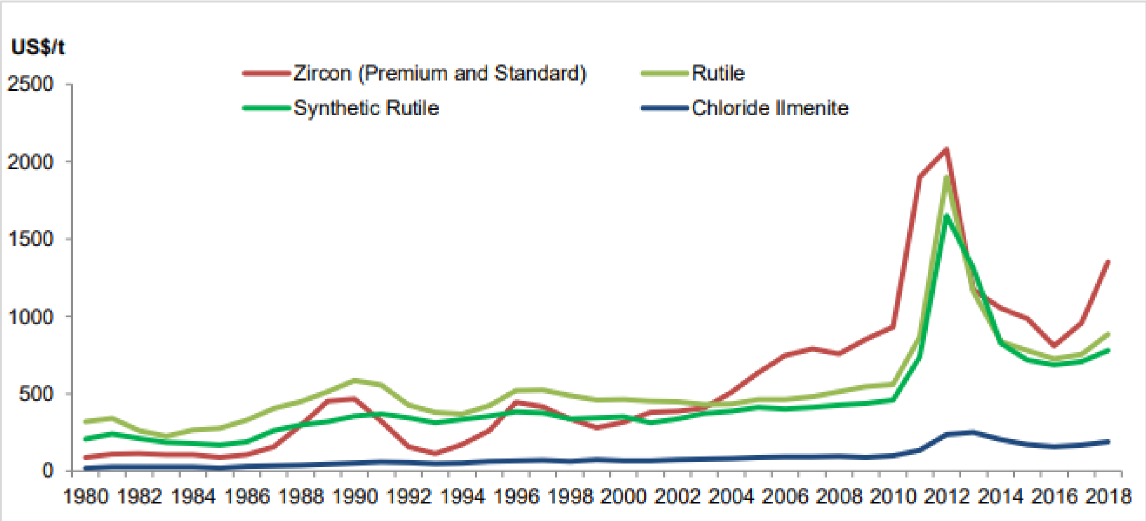


Figure 20. Mineral sands prices (Source: ILUKA, 2019).

The main driver for titanium mining is TiO_2 for the pigment industry, which consumes approximately 90 % of the globally mined titanium. An additional 5% is utilised to produce titanium metal and the remaining 5% utilised during welding as a flux in steel fabrication and ship building (ILUKA, 2019). Industry demand is correlated to GDP, urbanisation, construction and industrial activity.

5.3. Where is South Africa now?

The mining of titanium mineral concentrates and the upgrade to titanium slag (stage 1 & 2 of the titanium metal value chain) is well established in South Africa. The leading titanium mining companies are often responsible for upgrading the mined product before it is exported. The market dynamics of stage 1 and 2 of the titanium metal value chain as well as the different products produced during each stage will be discussed together in Section 5.3.1.

5.3.1. Market and Products (Where is South Africa now?)

South Africa is one of the largest producers of titanium bearing minerals. The country mines both ilmenite and rutile. Currently 100 % of the mined titanium mineral concentrates is exported. The bulk of the mined ilmenite is upgraded to titaniferous/titanium slag (USGS, 2018) and exported mostly to China. The top three local titanium mining companies all produce titaniferous slag via the smelting of ilmenite (Kotzé, Bessinger and Beukes, 2006). The tonnages over the last 10 years (till 2017), for both ilmenite (blue) and rutile (red) are displayed in Figure 21. Ilmenite accounts for 89% of the world's consumption of titanium minerals and is the primary titanium mineral mined in South Africa.

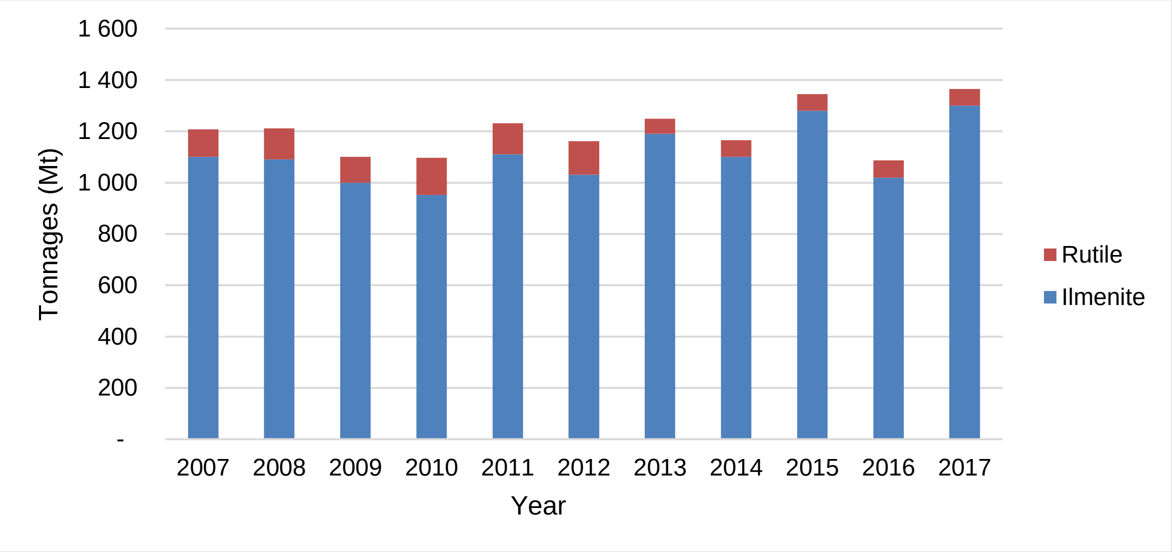


Figure 21. Titanium mining in South Africa in million tonnes (Adapted from: USGS, 2018).

The local leading titanium mining and upgrading companies are the Richard's Bay Minerals (RBM) Tisand, Exxaro Hillendale mine and the Namakwa Sands mine. RBM is located at Richards Bay in KwaZulu-Natal (KZN). This mining company is the leading producer of titanium slag, rutile as well as high purity pig iron. RBM is divided into a mining (Tisand) and smelting/beneficiation section (Richards Bay iron and titanium) and is the largest mining operation in the country (Motsie, 2008).

Namakwa Sands is located on the west coast of South Africa and has two smelter facilities at Brand se Baai and Saldanha Bay (Western Province). This mine also produces large quantities of mostly titanium slag but also pig iron and rutile (Motsie, 2008). Hillendale mine (near Empangeni in KwaZulu-Natal) as well as Namakwa Sands was formally owned by Exxaro but has recently sold their shares to Tronox which is a global leader in titanium mining and the manufacturing of TiO_2 pigments.

South Africa exports its titanium slag as well as other minerals mined with the titanium concentrates zircon, monazite and garnet (Motsie, 2008). The titanium mineral concentrates are used in several value added products such as pigment, plastics, batteries, functional fillers, chemical feedstock, super alloys, sporting equipment and medical application (Motsie, 2008).

South Africa does not produce synthetic rutile. A possible reason for this could be that the country is focusing on exports and according to Tyler and Minnittt (2004) the profit of pure rutile will be larger than for synthetic rutile. Natural rutile and upgraded slag are priced similarly. Tyler and Minnittt (2004) also mentioned that it is more expensive to produce synthetic rutile compared to upgraded slag, therefore it would cost more to produce synthetic rutile and it would bring in less profit compared to upgraded slag. Table 15 indicates the price (in Rand) of ilmenite, rutile and slag as well as the revenue made by South Africa from exporting these mineral concentrates during 2018 and 2019.

Table 15. Locally produced titanium mineral concentrates and the revenue generated (Adapted from: USGS, 2019).

Year	Mineral concentrate	Kilo tonnes produced (kt)	Tonnes produced (t)	Rand per tonne	Export sales in billions of Rand
2018	Ilmenite	765	765 000	2 279	1. 7
	Rutile	103	103 000	13 578	1. 4
	Slag	356	359 550	9 525	3 .4
2019	Ilmenite	820	820 000	2 487	2 .0
	Rutile	110	110 000	14 818	1 .6
	Slag	385	385 400	11 854	4 .6

Globally approximately 90 % of the titanium mined is consumed in the form of titanium dioxide (TiO_2) which is used as a white pigment in paints, plastics and paper. Figure 22 illustrates the difference in global production capacity of titanium sponge against titanium pigment for 2018. This is an important consideration for this stage of the value chain as it is the downstream market for titanium mineral concentrates. The high-grade feedstock is mainly used during sponge production and the bulk of the low-grade for pigment production. High-grade contains more titanium and less contaminants compared to the lower grade.

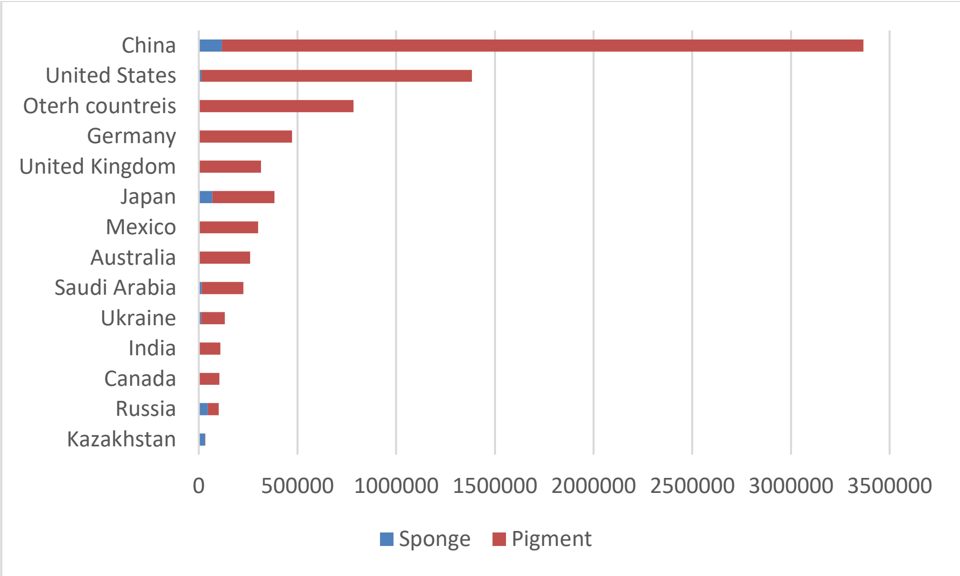


Figure 22. Global titanium sponge and pigment capacity (Adapted from: USGS, 2019).

Prior to 2016, the Huntsman Tioxide South Africa manufacturing facility had a 25 000 tpa pigment plant (Motsie, 2008). In 2016, Huntsman Tioxide decided to close the plant. At the time the South African plant was Huntsman Corporation's smallest and oldest TiO_2 manufacturing plant (commissioned in 1962). The plant closure envisioned a cost saving of approximately $200 million for Huntsman Corporation (Chapman, 2016). The Huntsman South African plant utilised the sulphate process for TiO_2 pigment production.

Titanium minerals are obtained from heavy mineral concentrates that contain titanium minerals such as rutile and ilmenite as well as zircon, iron, monazite and garnet (Motsie, 2008). The by-products obtained in addition to the titanium minerals contributes to making titanium mining feasible.

- Zircon is the commercial source of zirconium that is used in the ceramics industry and for blazing on tiles. It is recovered as a by-product from mining titanium rich heavy mineral concentrates. Once recovered zircon is exported as a commodity on its own.
- During the upgrading of ilmenite pig iron is also produced as a by-product.

Evraz Highveld Steel and Vanadium Limited produced steel form magnetite with a high titanium content. The result was that sufficient amounts of titanium (together with vanadium) was discarded as slag. Although this plant is no longer operational the slag is still being investigated as a source of titanium and reprocessed as a source of vanadium (Reporter, 2018). One of the companies that most recently showed interest in this slag is Nyanza Light Metals and they will be discussed in more detail in the R&D section of this chapter (Section 5.3.3).

5.3.2. Technology (Where is South Africa now?)

The technologies used to mine and upgrade titanium mineral concentrates are established technologies. The most popular heavy-mineral sands mining techniques are dredging and dry mining. Once mined gravity spirals are used to separate the heavy minerals which are then further separated by magnetic separation and high tension separation circuits (Motsie, 2008).

In order to upgrade ilmenite to chlorinatable feedstock, electric smelting needs to occur to produce titanium slag (opposed to the Bencher process). The two melting routes followed in South Africa are direct current (DC) arc furnaces and AC furnaces (Kale and Bisaka, 2016; Bisaka, Thobadi and Goso, 2016).Smelting lowers the iron content of the ilmenite by the reduction of iron oxide to its metallic state at around 1 650°C. The two products produced during this process is titanium-rich slag and molten iron (Pistorius, 2008). It should be noted that Kotzé, Bessinger and Beukes (2006) stated that although the majority of the technologies are old and established, limited sharing of metallurgical process or marketing information is shared between companies as the whole industry (mining up to pigment or metal production) is highly competitive.

5.3.3. Research and Development (Where is South Africa now?)

According to Pistorius (2008) the basic approach to ilmenite smelting has remained quite consistent since it was first implemented and no major process changes are anticipated. Pistorius however lists several areas where improvements could be applied to the furnaces such as energy efficiency, lowering of heat loss and improved furnace design.

One of the key players in researching titanium feedstock in South Africa is Mintek. Mintek is South Africa's national R&D organisation on minerals technologies. Mintek has been involved in titanium feedstock research since the early 1970s and still actively researching in this field today (Kale and Bisaka, 2016). Mintek, together with Anglo American, developed the DC arc smelting process currently used by all Tronox-operated plants in South Africa (Kale and Bisaka, 2016).

One of the biggest movements in the South African upstream titanium industry is driven by the Nyanza Light Metals plant. This plant will produce titanium dioxide pigment and aims to replace the gap left by the Huntsman Trioxide pigment plant that closed down in 2016 (Nyanza Light Metals, 2017). Nyanza Light Metals has partnered with a New Zealand company, Avertana and aims to construct a pigment plant with a 100 ktpa capacity. The feedstock for the plant will be waste slag from Evraz Highveld Steel and Vanadium limited. The slag contains low quantities of TiO_2 (32 – 45 %) and will be purified using a novel technology supplied by Avertana.

The project has been split into three phases with the first two phases employing the sulphate route to produce pigment and the third phase aims to beneficiate rutile following the chloride process (Nyanza Light Metals, 2017). Although this process does not produce titanium metal, the successful application of this technology will develop relevant skill sets in South Africa that could be beneficial to the developing titanium metal industry.

5.3.4. Resources (Where is South Africa now?)

Each of the results chapters (Chapter 5 to 11) will discuss resources twice. First the current available resources (Where is South Africa now?) and then the future resources (How will South Africa get there?). According to the methodology section (Section 4.4.2) two main resources will be discussed namely the availability of raw materials (feedstock for the stage being discussed) and the human capital being developed though the stage. A third resource that will only be discussed in Chapter 5 as it is relevant to all of the results chapter is electricity. As electricity is supplied from the same country and source it will not vary greatly between the value chain stages and will therefore only be discussed in this chapter (Chapter 5) under a separate sub-heading called Energy as a local resource (Section 5.3.4.1). Energy will however be included in the roadmaps for each of the value chain stages.

The 2019 USGS reported combined reserves for ilmenite and rutile in South Africa are 41 100 kt (USGS, 2019). Except for the large titanium mineral reserves several other valuable minerals are obtained from titanium mining such as zirconium, iron and vanadium. South Africa has a long mining history and this historical mining knowledge is a significant benefit. Together with the rich mining history, the country has developed world renowned industrial skills in the field.

5.3.4.1. Energy as a Local Resource

The bulk of the local electricity is generated from coal fired power stations. This is a cheap form of electricity and according to Businesstech (2019) South Africa has relatively cheap electricity compared to the rest of the world (see Figure 23). This is however not the case when comparing costs with other emerging markets. Countries such as Argentina, Turkey, Indonesia, China, India and Russia report cheaper electricity.

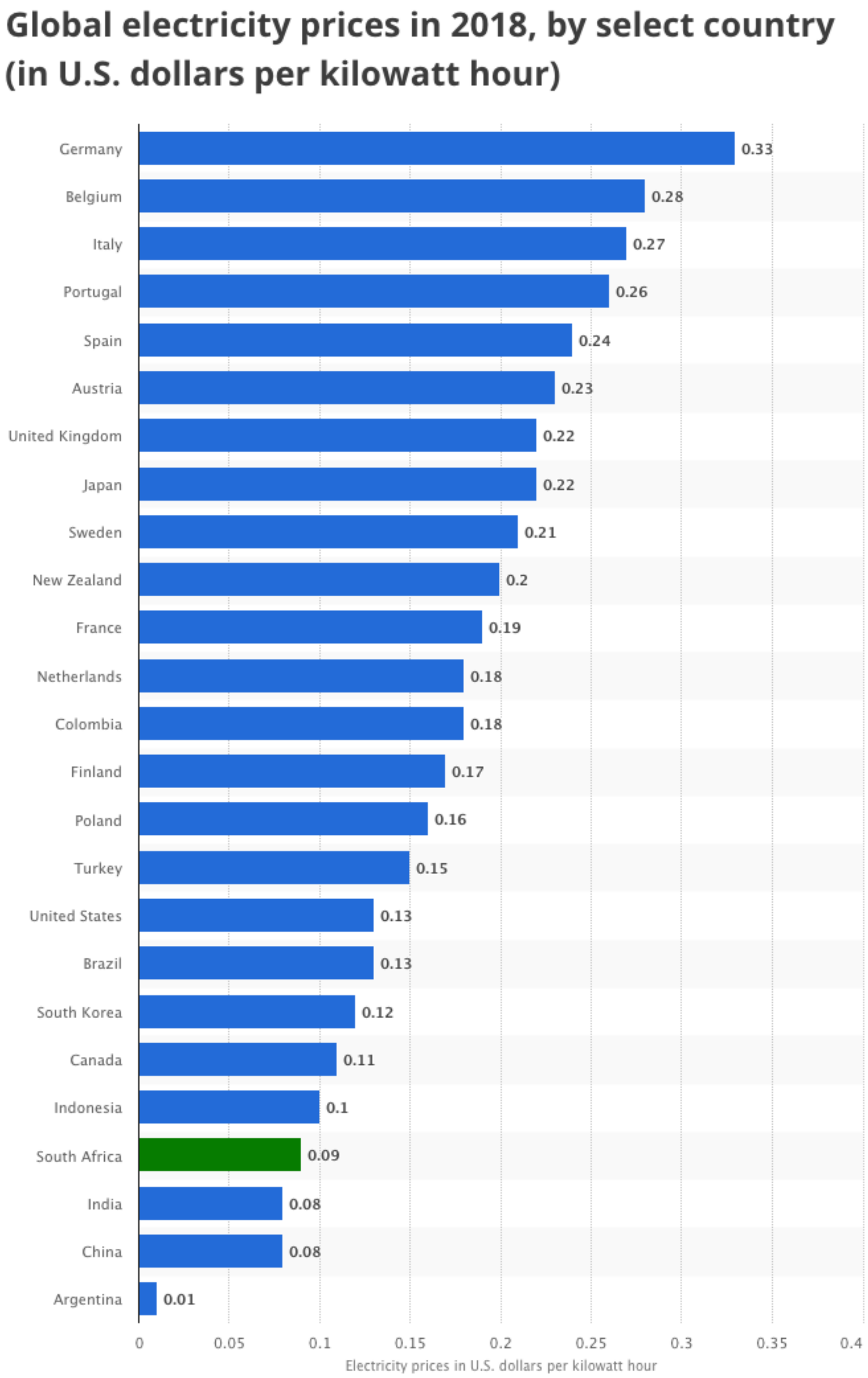


Figure 23. Global electricity prices for 2018 as per Statista, a German statistics portal for market data (Source: Businesstech, 2019).

Although the country's cheap electricity can be viewed as a resource it comes with its own set of challenges. South Africa started facing electricity problems in 2008 that resulted in the country not being able to supply industry with enough and reliable electricity. Government has produced two main plans to correct the problem.

The first is the aligned with the Integrated Resource Plan (IRP) renewable energy outlook that would meet the expected demand growth up to 2030 (Department of Energy, 2018). The second plan was presented in the 2020 State of the Nation Address (SONA) where South Africa's President, Cyril Ramaphosa, stated that the state supports the rapid and significant increase of generation capacity outside the state-owned entity, Eskom. This will make it easier for independent electricity producers to get certification to build and run plants above 1 MW (Cronje, 2020). Allowing companies to generate their own (and surplus) electricity will drive companies to become more independent and sustainable.

Several interviewees indicated that the production stages of titanium metal is energy intensive and they highlighted the need for companies to consider incorporating privatised renewable energies into their energy mix. Interviewees suggested using solar power (concentrated solar power or photo voltaic) to lower the reliance on Eskom power (South Africa's solo power producer). Globally South Africa has been identified as one of the countries with a large potential to utilise solar energy. The country has an average of 2 500 hours of sunshine per year with an average direct solar radiation level of between 4.6 and 6.5 kWh/m^2 per day (Department of Energy, 2015). The process of implementing renewable energy would be more accessible and be beneficial to creating a more stable electricity grid leading up to 2030.

The shortage of electricity is posing a dangerous risk to the development of the titanium metal value chain. An example of this is that stages of the value chain (e.g. stage 2) might become uneconomic due to unreliable and expensive electricity. In a news article published by ENCA (2019) the Ferro Alloys Producers Association of South Africa (FAPA) stated that load shedding is leading to production losses and if this continuous job losses would be inevitable. The processing and smelting of metal-bearing ores are high energy intensive processes. During mineral upgrading ilmenite smelting occurs in the DC arc smelting process. The smelters are heated up to around 1 650 °C to melt out the iron and thereby lowering the iron content of the ilmenite. The products formed are a value-added titanium-rich slag and molten iron. Unreliable electricity supply caused by load shedding can cause companies to reassess their smelting operations which might lead to smelters closing and moving this stage of the value chain to an offshore location. Another factor that should be considered in the future is the possibility for unit price increases. As South Africa implements the IRP and renewable energies are added to the mix the energy price is increasing and this could also cause companies to take their business offshore.

5.3.4.2. Energy Consumption During Titanium Metal Production

In 2017, the US Department of Energy (DOE) Advanced Manufacturing Office delivered a report on the energy saving opportunities for six structural materials including titanium alloys. The report on titanium alloys reported on the energy consumed for the production of titanium mill products (Energetics Incorporate, 2017). This study was used to determine the energy consumption of the US titanium metal industry. Limited amounts of titanium minerals are mined in the US therefore the study excluded the mining and upgrading of titanium mineral concentrates (stage 1 and 2 of the titanium metal value chain). The study was further also only conducted on the conventional titanium metal value chain and therefore, excludes stage 7 (titanium powder production) and stage 8 (titanium powder products). The energy consumption (in percentage) for stage 3 to stage 6 is displayed in Figure 24.

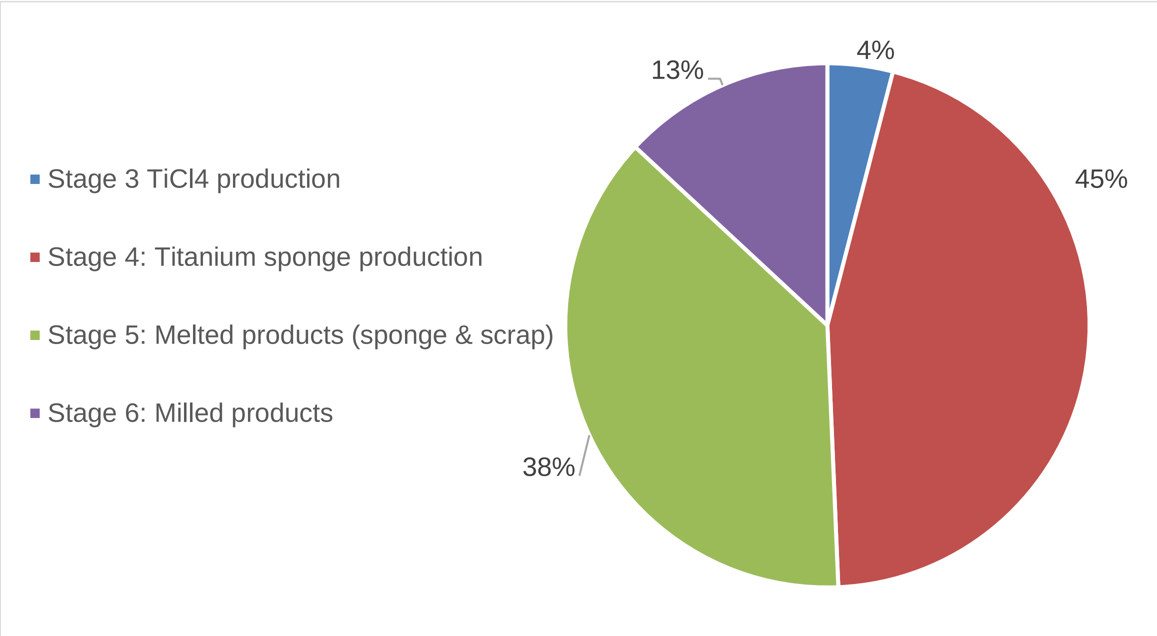


Figure 24. A percentage representation of the onsite energy intensity for titanium manufacturing (Adapted from: Energetics Incorporate, 2017).

From Figure 24 the value chain stage that requires the most electricity in decreasing order is titanium sponge production (stage 4 in red), melted product production (stage 5 in green), mill product production (stage 6 in purple) and $TiCl_4$ production (stage 3 in blue). The study conducted by Energetics Incorporate (2017) did not include the first two and the last two stages of the titanium metal value chain. Experts did however indicate that the electricity use for the first two stages (titanium mining and slag production) is expected to be similar to melted product production as it also include melting. The electricity use for the last two stages of the value chain is unknown as there are various technologies that can be applied to produce titanium metal powder (stage 7) and titanium metal powder products (stage 8).

5.4. Vision element: Where does South Africa want to go?

The vision element for titanium minerals reserves and titanium slag production, two stages that are at high maturity, is that the country should continue to mine and upgrade titanium mineral concentrates at a sustainable and efficient manner.

This vision element was confirmed by the survey that was sent out for this research. 100 % of the answers agreed with this vision element. Additional comments to note are that an increase in mining is not a requirement for the next decade. Enough resources are currently being mined to satisfy the market and therefore increasing production tonnes are not necessary. Interviewees expressed their concern that titanium resources could be depleted in less than 50 years if mining continues at the present rate.

5.5. How will South Africa get there?

For the next three years, approximately 70 % of the interviewees indicated that local titanium mining would increase. This dropped to 45 % when the interviewees were asked if the local titanium mining industry would still grow in 10 years. For the 10 year vision element 40 % of interviewees predicted that growth in titanium mining would level out. The remaining 15 % stated that there would be a reduction in titanium mining within the next 10 years. The reasons for the initial increased mining activity was attributed to:

- the growth in the zirconia market,
- the annual growth in the pigment market (±3% per year),
- new mining areas coming online,
- increased mining tonnages due to lower grade titanium concentrates requiring larger mined tonnes,
- the implementation of improved and more efficient beneficiation technologies being able to recover more product while using less electricity,
- increased market size with the addition of a local chlorination plant (maintain original export footprint), and
- Evraz Highveld Steel and Vanadium Limited slag to become a resource once a technology to process it has been developed.

Reasons provided for the decrease or stabilising in mining in the longer term were:

- political instability,

- environmental legislation due to mining of beaches in environmentally sensitive areas,
- mines moving to new areas but retaining the same footprint,
- socio-economic problems in rural areas halting mining expansion,
- the price as well as confidence in electricity supply making operations uneconomical,
- reduced mining to only supply titanium mineral concentrates to process and supply local demand, and
- there are no plans to build any new smelters, therefore the smelting capacity would remain the same.

It was however concluded that a growth in local mining capacity is not a requirement for these two stages as enough resources are available and the market demand satisfied. It is therefore expected that titanium mining and the production of upgraded products will remain constant for the next decade.

5.5.1. Market (How will South Africa get there?)

The current and future marketable products from this stage of the value chain are rutile, ilmenite and upgraded titanium (slag). The biggest global market for upgraded titanium is the titanium pigment industry that processes approximately 90 % of the globally mined titanium ore for this industry (growing at 3 % per year) (ILUKA, 2019). According to the interviewees, South Africa should consider developing the titanium metal industry in conjunction with the titanium pigment industry, otherwise the market would be too small to justify building a chlorination plant locally. The feasibility of a local chlorination plant will be discussed in more detail in Chapter 6.

When considering the overall vision for the South African titanium industry, the future market for titanium mineral reserves and slag production should include a portion of the products being consumed locally. A portion of the locally mined minerals would then be chlorinated to produce a feedstock to produce titanium dioxide (pigment) as well as titanium metal. The main drivers for this would be South Africa investing in a titanium pigment plant, or a breakthrough in direct powder production.

5.5.2. Product (How will South Africa get there?)

After mineral beneficiation the products from mining (stage 1 of the titanium metal value chain) are rutile and ilmenite. Rutile is sold as a commodity, but ilmenite is first upgraded to titanium-rich slag and pig iron. The interviews revealed a concern that highlighted the risk of South Africa losing the ability to upgrade ilmenite (value addition) based on the unreliability and cost of the electricity supply. Once it becomes more feasible to export ilmenite and beneficiate it further internationally

South Africa might lose the value adding step of the titanium metal value chain (stage 2). Instead of losing this stage, South Africa should aim to produce a higher quality slag that is chlorinatable and could be exported at a higher cost.
The “by-products” obtained when mining for titanium will always play a crucial role in the profitability of this stage of the value chain (vanadium, zirconium, garnet and iron). Vanadium is used for steel applications (alloys), in batteries and as a mordant (material that fixes dyes to fabrics). Although some of the vanadium in the Evraz Highveld Steel and Vanadium Limited slag is already being recovered this might be done on a larger scale in the future if the price is right.

5.5.3. Technology (How will South Africa get there?)

Although the technologies utilised during titanium mineral concentrate mining and upgrading (stage 1 and stage 2 of the titanium metal value chain) is well developed and understood, South Africa could still benefit from applying small alterations to the technology. South Africa needs to invest in more efficient smelting systems and processes that require less water. These technologies could reach the energy targets while generating minimum waste (circular economy). Achieving these efficiencies will be the main driver behind R&D for the next decade.

5.5.4. Research and Development (How will South Africa get there?)

The results obtained from this study indicates that South Africa is expected to produce $TiCl_4$ locally within the next decade (see Chapter 6). This will open a local market for the titanium mineral concentrates as they will be used as feedstock for the $TiCl_4$ plant. R&D should be started around the logistics of using the locally mined titanium mineral concentrates (ilmenite slag and rutile) as feedstock for the local $TiCl_4$ plant.

There is also a need for R&D to continuously develop more efficient technologies. This research should expand to add renewable energy sources on site to lower the dependence on electricity sourced from Eskom. According to the interviewees mining companies are already investigating customised processes of producing energy on site to lower the dependence on Eskom.

5.5.5. Resources (How will South Africa get there?)

In mining a circular economy is described as the industry making use of high performance and durable products (ICMM, 2020). These products are used with the optimal utilisation of raw materials such as the intelligent re-use of any waste products. Titanium mining produces several by-products and, in the future, this needs to be increased and accelerated making sure that all the valuable minerals are extracted during the first process run.

Production of titanium mineral feedstock is not driven by local demand. According to the 10 year vision South Africa should be processing some of its local titanium mineral concentrates within the next decade. Once this local market has been established, South Africa should have access to titanium minerals such as rutile, ilmenite as well as titanium rich slag. This means that the country is dependent on the next step on the value chain to consume the resources for both the titanium pigment and titanium metal industries.

5.6. Discussion: Roadmap for Ti Mineral Reserves & Slag Production

The methodology presented in Chapter 4 was used to generate a roadmap for each stage of the titanium metal value chain. As per this methodology the information discussed under the results sections in Chapters 5 - 11 were collected from interviews, a survey, as well as secondary sources. The aim of the interviews was to obtain the vision element for each stage of the value chain from experts involved in that specific stage (resulted in multiple vision elements). The survey was the final filtering system applied to identify a single vision element for each stage. The reason for developing a roadmap for every stage is contributed to the fragmented nature of the titanium metal value chain in South Africa. Each stage should be able to stand on its own and therefore develop on its own or not, depending on the stage's vision element. An overall roadmap will also be generated to visualise the "Roadmap for the South African titanium metal industry". This will be discussed in Chapter 13.

Each of the results chapters follows the generic technology roadmap model that considers "Where is South Africa now?", "Where does South Africa want to go?" and "How will South Africa get there?". Table 16 is the summary of these questions and answers obtained in Chapter 5. The information contained within this table was used to produce the roadmap for both stage 1 and stage 2 of the titanium metal value chain (titanium mineral reserves and slag production) as shown in Figure 25.

Table 16. Summary of titanium mineral reserves and slag production (stage 1 and 2).

Where is SA now?	Market	• South Africa exports 100% of its mined titanium • Titanium is exported in the form of natural rutile and upgraded titanium slag (from ilmenite)
	Product	**Products from mining:** • Ilmenite is upgraded into titanium slag • Natural rutile • By-products: zircon, vanadium and iron • Waste steel slag with high titanium and vanadium content historically produced by Evraz Highveld Steel and Vanadium Limited
	Technology	**Mining techniques:** • Dredging • Dry mining **Separation techniques** • Gravity spirals • Magnetic separation • High tension separation circuits **Ilmenite upgrading** • Ilmenite smelting route, DC and AC arc smelting (all of the above: **Established technology**)
	R&D	• Improvements to smelting furnaces, such as energy efficiency, lowering of heat loss and improved furnace design • Nyanza Light Metals' sulphur pigment production process
	Resources	• Large titanium concentrate reserves that also contains zircon, vanadium and iron • Relatively cheap electricity compared to first world countries. • Historical mining knowledge and mining skills
Where does SA want to go?	Vision element	*The vision element for titanium minerals reserves and titanium slag production, two stages that are at high maturity, is that the country should continue to mine and upgrade titanium mineral concentrates at a sustainable and efficient manner*
How will SA get there?	Market	• The export market will dominate this stage of the value chain • Local market potential could result from set up of a pigment plant and local production of $TiCl_4$ • Set up of Nyanza Light Metals will create a local market for waste steel slag historically produced by Evraz Highveld Steel and Vanadium Limited
	Product	**Products from mining:** • Ilmenite that is upgraded into titanium slag • Natural rutile • By-products: zircon, vanadium and iron
	Technology	• Established technology (see technology section above) • Improved efficiency during mining, separation and upgrading • Environmentally friendly and circular economy • Nyanza Light Metals sulphur process to produce pigment
	R&D	• R&D on efficient technologies and product optimisation • R&D on integrating renewable energy sources

		• It is expected that South Africa will produce $TiCl_4$ locally within the next decade. This means that the 100 % export of titanium mineral concentrates will change. R&D is needed to prepare the localisation of the use of titanium mineral concentrate
	Resources	• Large titanium concentrate reserves that also contains zircon, vanadium and iron • Relatively cheap electricity & an increase in renewable energy • Historical mining knowledge and mining skills

Table 16 summarises the results collected for each of the generic roadmap layers and was used to generate the roadmap for titanium mineral reserves and slag production (stage 1 and 2 of the titanium metal value chain). Each layer will be displayed on the roadmap for a time period of three years and seven years (total of ten years).

In the methodology section the roadmap design and construction were explained (Section 4.4). Each roadmap was constructed using the different roadmapping layers. These layers can interact with each other as presented by arrows indicating what themes (blocks within each layer) or layers are linked. Thick arrows indicate interaction with different layers and thin arrows interaction of themes within the same layer. The arrows indicate a dependence of themes and layers as the next theme could only be started once the prior theme has been achieved. As with the generic roadmapping structure the themes adheres to time on the roadmap's x-axis and systematically progress to the overall vision element displayed on the right-hand side of the roadmap.

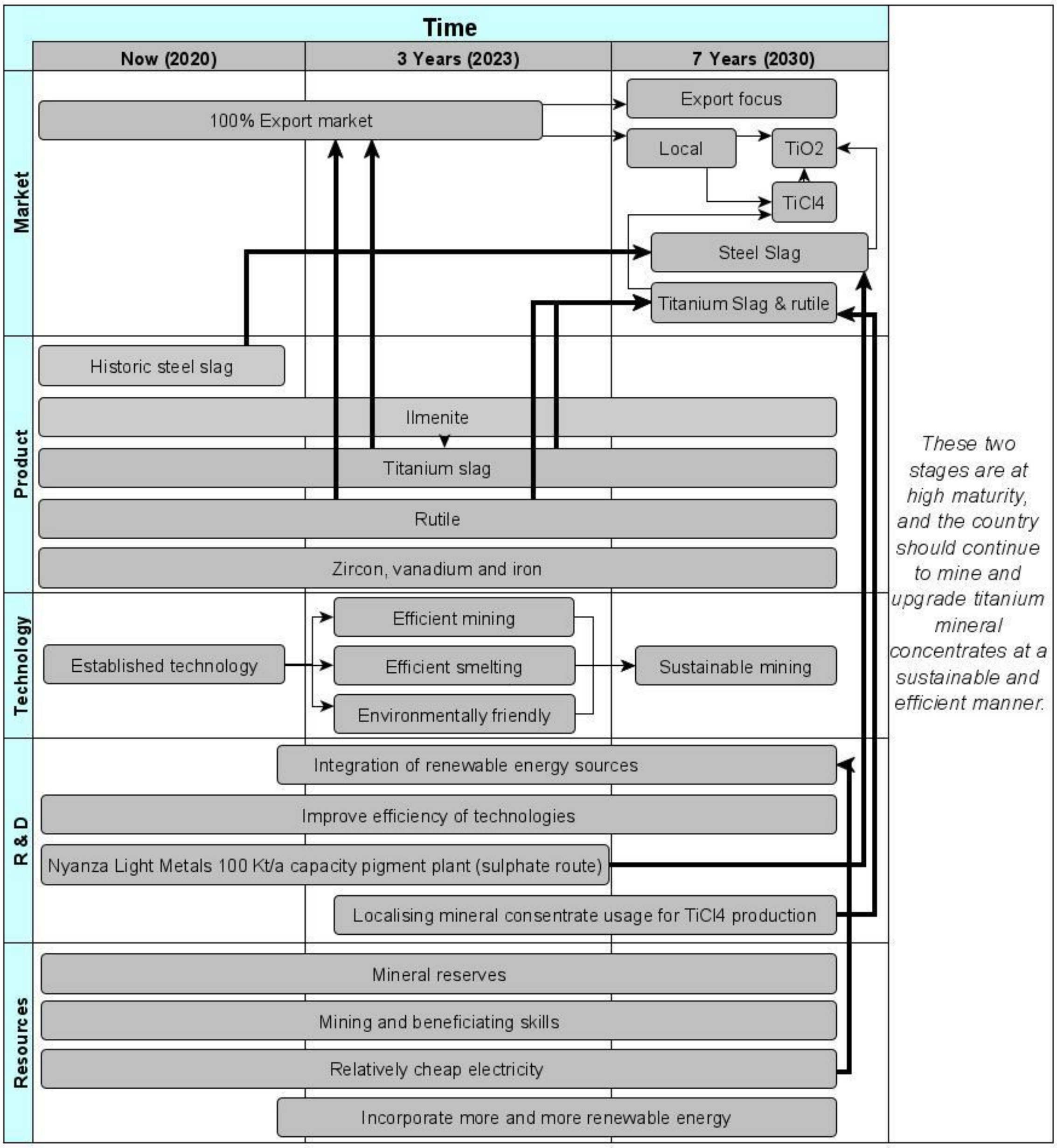


Figure 25. The local 10 year roadmap for titanium mineral reserves and slag production (stage 1 and 2).

The first two stages for the local titanium metal value chain (titanium mineral reserves and slag production) were displayed on the same roadmap (Figure 25). The reason for this is that the mining as well as the upgrading falls under the same company and are mostly confined to the same physical site. Titanium mineral concentrates are mined and undergo separation processes to produce titanium bearing minerals namely ilmenite and rutile. Ilmenite has a lower titanium content compared to rutile and first needs to be upgraded. The upgraded product from ilmenite (now with a higher titanium content) is titanium slag.

All the slag and rutile produced locally goes into the export market. It is expected that this 100 % export of rutile and titanium slag will continue for the next three years as there are no local demand for the products. The value chain vision element for the next stage of the titanium metal industry (stage 3, $TiCl_4$ production) indicates that within the next decade this will change. This change will be driven by the pigment industry rather than the titanium metal industry. The vision element for stage 3 ($TiCl_4$ production) indicates that South Africa should be producing pigment through either the chloride or sulphate route within the next decade. The chloride route would also open the titanium metal market (as $TiCl_4$ is used as feedstock) where the sulphate route results only in pigment production.

In addition to ilmenite and rutile other by-products are also obtained for the heavy mineral concentrates. The main economic products are zircon and iron. Vanadium is also obtained from titanium rich waste dumps that originates from steel production. Waste steel slag that was produced by Evraz Highveld Steel and Vanadium Limited prior to 2016 is also seen as a local titanium product that could be further processed for titanium (mainly pigment) production.

The technology used to mine and upgrade the heavy mineral sands are established and the industry is mature in South Africa. Based on the maturity of the technology not a lot of technological changes are expected in the next decade, except for the industry making changes to the efficiency of mining and upgrading (such as the smelting process). The changes will be aimed at being more environmentally friendly to ensure a sustainable mining future of this commodity while protecting the environment.

The R&D conducted on these two stages are aimed at improving on the efficiency of the existing technologies. Current research is focusing on improving furnace designs to reduce heat loss and ultimately be more energy efficient. Another way to use resources more efficiently is to integrate the use of renewable energy into the systems. R&D on a national scale is focusing on the integration of renewable energy sources into industry as a more environmentally friendly option as well as ensuring a stable supply of energy. Additional research by Nyanza Light Metals is investigating the feasibility of reworking the Evraz Highveld Steel and Vanadium Limited waste dumps utilising the sulphate process to produce titanium pigment. This process aims to follow the sulphate route for pigment production. Based on stage 3's titanium metal value chain vision element ($TiCl_4$ production) some of the locally mined titanium products (titanium slag and rutile) will be consumed locally within the next decade. A need has therefore been identified to conduct studies on how the localisation of titanium mineral concentrate usage will affect the first two stages of the titanium metal value chain (titanium mineral reserves and slag production).

As mentioned in Chapter 4 resources include raw materials (or feedstock), human capital and electricity. South Africa has the fourth most abundant titanium mineral reserve and titanium mineral concentrate mining will continue past the timeframe of this study (past 2030). Titanium mining and beneficiation has been conducted in South Africa for a long time and employs several skilled and unskilled employees. In remote areas (such as the Namaqua sand mine) the titanium industry is an important source of income for the local area. South Africa is also known as a country with rich mineral reserves with a well-established mining industry and has thus historic mining knowledge, as well as sufficient mining skills. South African businesses pay less for electricity compared to several first world countries. This resource has been compromised during recent years as Eskom struggles to supply stable and reliable electricity to the country. The local vision for the South African electricity supply is that this problem should be eliminated by 2030 and that renewable energy would play a bigger role in the energy mix.

5.7. Chapter Summary

Titanium bearing minerals are found on all continents, but only a few countries have sufficient high-grade titanium mineral reserves that can be mined economically. South Africa is one of these countries and mines heavy mineral sands that produce titanium mineral concentrates, as well as other valuable commodities. Locally the country adds value to ilmenite by upgrading it through a smelting process to titanium slag that contains a higher titanium content. Upgraded titanium slag and rutile (naturally high titanium content) are then exported to other countries for further processing, mainly to produce titanium pigment.

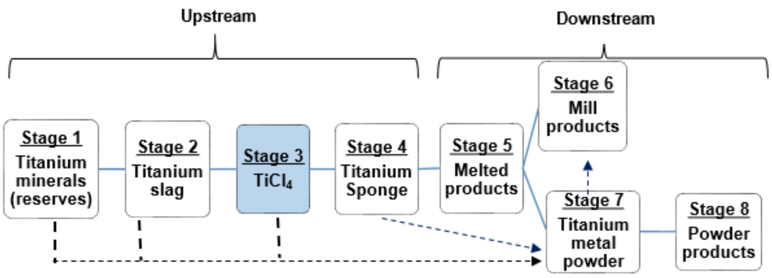
Currently 100 % of the mined rutile and upgraded titanium slag is exported. The vision element that drives the roadmap (shown in Figure 25) for the first two stages of the titanium metal value chain aims to localise the use of at least some of the titanium feedstock. This will be achieved by the country either investing in a $TiCl_4$ production plant (feedstock for both the pigment and metal market) or the development of a pigment plant via the sulphur route (Nyanza Light Metals).

The mining and upgrading of heavy mineral sands are an established industry in South Africa and the country has built a substantial knowledge in this industry. Challenges experienced by this industry includes an unreliable electricity supply and inefficient older technologies (such as the smelters). R&D within these stages is aiming to improve on these technologies making them more energy and water efficient as well as enforcing sustainable mining.

A constant balance between mining opportunity and new mining areas (regarding environmental concerns) remains an important issue to be addressed in South

Africa. One such an environmental driven issue that occurred recently involved an Australian mining company that wanted to open a titanium mine in an environmentally sensitive area called Xolobeni on the Wild Coast in the Eastern Cape province of South Africa. This mining venture was opposed by the local community not standing back for big international companies destroying their environment. By time of completing this study the case was still ongoing.

6. Chapter 6: Stage 3 ($TiCl_4$)



6.1. Literature Review

$TiCl_4$ is a colourless liquid with a boiling point of 136 °C (Bordbar, Yousefi and Abedini, 2017). This compound has globally been accepted as the preferred precursor for both titanium pigment and titanium metal production. $TiCl_4$ is not only limited to pigment and titanium metal production, but is also used as a catalyst to speed up the polymerisation of olefins even at mild conditions (Bordbar, Yousefi and Abedini, 2017).

$TiCl_4$ is produced through either the chloride or the chloride-ilmenite process. The difference between the two processes is related to the quality of the feed material. Rutile, synthetic rutile and high-purity ilmenite are used as feedstock for the common chloride process and low-purity ilmenite is converted to $TiCl_4$ through the chloride-ilmenite process. The chloride-ilmenite process requires a two-stage chlorination process with adjustments to the feed rate, the quantities and the operating parameters (Dooley, 1975; EPA, 1995). $TiCl_4$ obtained from the chloride process is used for the production of titanium sponge(also referred to as the direct fluidised bed chlorination process) (EPA, 1995).

6.1.1. Direct Fluidised Bed Chlorination Process

This type of chlorination is typically done in a vertical shaft furnace. The operating conditions should be between 800 - 1 000 °C and the pressure slightly above atmospheric pressure. The following approximate chlorination steps were described by Dooley (1975):

1. Either rutile or ilmenite is poured into a chlorination column and chlorine gas is passed through. The solids are fluidised by the flow rate of the chlorine
2. A reducing agent is also added into the reaction chamber. This is normally carbon as either coke or coal. The reducing agent is added to bind the oxygen from the metal oxide in the ore.
3. The conversion process is more complete for rutile (±94-96 % TiO_2) and could reach up to 100 % conversion to $TiCl_4$. Ilmenite contains a bit more contaminants (±60 % TiO_2) and therefore approximately 90 % of the ilmenite is converted to $TiCl_4$.

4. In a controlled system (minor heat losses), the reaction between the carbon and chlorine is sufficiently exothermic and maintains the temperature between 800 - 1 000 °C.
5. Oxygen is introduced to the system with the chlorine to supply starting or auxiliary heat.
6. $TiCl_4$ is captured in from the top portion of the reaction zone and is in a gaseous phase at this stage.
7. This gaseous phase also contains ferric chloride and other chlorides as contaminants.
8. The gaseous mixture exits the chlorinator and the sublimated solids are separated from the $TiCl_4$.
9. The $TiCl_4$ is further purified to further remove contaminants.

Different contaminants within the feedstock will be chlorinated together with the titanium. Of these contaminants iron and vanadium are the most difficult to remove. During the fluidised process iron is removed during the separation step, vanadium on the other hand is removed as a part of the purification stage (Dooley, 1975).

Once again, a difference in the processing of rutile and ilmenite can be observed. Rutile naturally has less contaminants, especially iron, than ilmenite, but generally contains larger amounts of vanadium. To remove the iron means that the chlorination of ilmenite will need additional and prolonged separation stages as well as plant capacity for treating the larger quantities of iron chloride that will form as by-product (Dooley, 1975). The ideal would be to recycle the chlorine from the iron chloride back into the system to reuse the chlorine.

In order to remove the vanadium, additional chemical treatments are required to convert vanadium oxy-trichloride ($VOCl_3$) into a compound with a different boiling point (Dooley, 1975). This is necessary since the boiling point of $VOCl_3$ is very close to that of $TiCl_4$. Contaminants therefore lead to additional costs that should be considered for both rutile and ilmenite production (Dooley, 1975).

The chlorination process for rutile and ilmenite have slightly different chlorination reactions with the main aim to produce the purest possible product. The reaction kinetics are not shown in this thesis and can be observed in Bordbar, Yousefi and Abedini (2017). $TiCl_4$ has been identified as the precursor to the titanium industry and is a critical link in the titanium production chain as the purity of the $TiCl_4$ will influence the purity of the final product (Woodruff and Bedinger, 2013). A comparison between the chloride and sulphate route is provided in Figure 26. The end product in Figure 26 is pigment, but also indicates where the titanium metal section would start from $TiCl_4$ as feedstock.

6.1.2. The Sulphate Process

The sulphate process is not used to produce titanium metal, but only for titanium pigment, as $TiCl_4$ is required for metal production. This process dominated the titanium pigment plants till 1958 but currently the split is approximately 50/50 with the bulk of the new plants applying the chlorination process (TZMI, 2012). Compared to the chloride process the sulphate process produces larger amounts of acidic waste that requires acid recovery. This process also requires more labour and energy (Motsie, 2008; EPA, 1995). Chlorination technology on the other hand is more difficult and the initial capital costs are higher (TZMI, 2012).

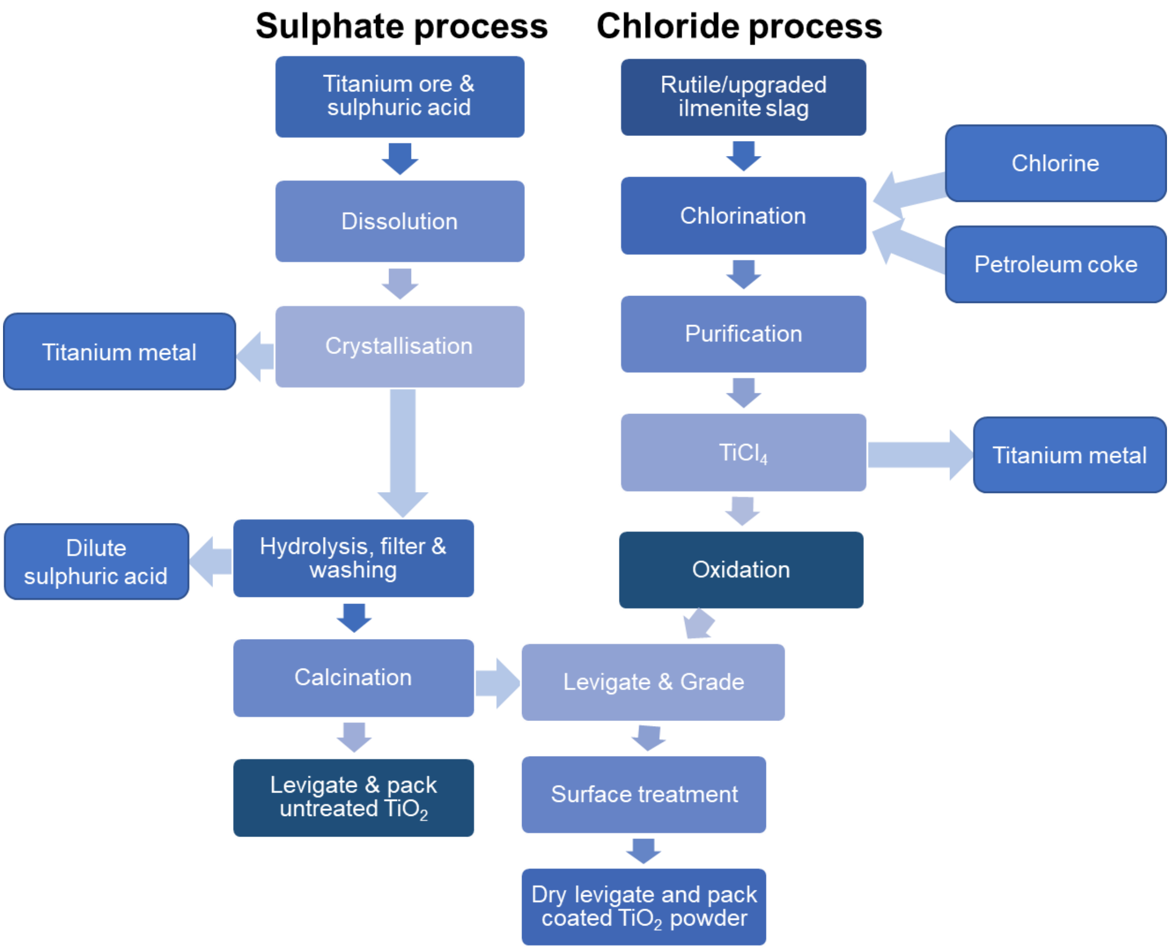


Figure 26. Comparison of the chloride and sulphate processes (sulphuric acid process) (Fangyuan Titanium Industry, 2020).

Titanium pigment is used for paints, coating, adhesives, paper, plastics, rubber, printing inks, coated fabrics and textiles, ceramics, floor coverings, roofing material, cosmetics, toothpaste, soap, water treatment agents, pharmaceuticals, food colorants, automotive parts, sunscreen and as a catalyst.

6.1.3. Economic and Environmental Concerns

The purity of the titanium source material (ilmenite, rutile or synthetic rutile) is of the utmost importance and holds economic consequences. As mentioned in the sections above, some trace elements cannot be removed and lowers the titanium end product strength. Another economic restraint is the large quantities of iron chloride ($FeCl_x$) produced during the chlorination process. The first material to consider is the chlorine used to produce the $TiCl_4$. Chlorine gas is expensive and introduces a range of environmental constraints. The chlorination process, on its own or integrated in the Kroll process, has therefore evolved to include systems that recover and recycle the chlorine, as well as the reductant (Dooley, 1975). Matsuoka, Mineta and Okabe (2004) state that although chlorine is re-circulated to be used in the chlorination and reduction process, there are significant amounts of chlorine waste being generated. The disposal of the chlorine is both painstaking and expensive. The loss of chlorine could create a chlorine gas deficiency, during chlorination, and additional chlorine gas should then be purchased. Chlorine wastes are environmental hazards as no efficient method exists for recycling (Matsuoka *et al.,* 2004).

Except for the research on finding a cheaper method to produce titanium powder, another focus point is the research to effectively recover chlorine during the chlorination process. Once this chlorine waste disposal problem can be minimised or even solved, then the purity of the titanium source material could be reduced and even low-grade titanium ore (or scrap) could be chlorinated (Dooley, 1975; Matsuoka *et al.*, 2004).

6.2. Global Outlook: $TiCl_4$ Production

The top four countries controlling the $TiCl_4$ trade are the USA, Japan, China and Russia. From these countries the key players are for the USA: Chemours, CRISTAL, Kronos, Tronox and Huntsman; for Japan: Ishihara, Toho Titanium and Osaka Titanium Technologies and for China: Ansteel, Xinmao Titanium, Xiantao Zhongxing Electronic Materials, Yunnan Xinli Non-Ferrous Metals, Huaxing Titanium and Zirconium, Henan Longxing Titanium, Haihua Industry Group and Cangzhou Heli Chemicals (InForGrowth, 2019).

The bulk of the globally produced $TiCl_4$ is utilised in the chemical industry to produce pigment or titanium metal. In this process the $TiCl_4$ acts as an intermediate feedstock in chemical processes resulting in the $TiCl_4$ to be utilised on site and limiting the trade of the material. Other uses for $TiCl_4$ are in the manufacturing of catalysts, as well as for a chemical to treat glass and metal surfaces (InForGrowth, 2019). $TiCl_4$ is seen as a hazardous chemical and therefore the logistics around transport is complex. Some of the above-mentioned companies do specialise in $TiCl_4$ transport.

The $TiCl_4$ industry displays an historic upwards growth curve with the current growth indicated at 4.1 % until 2026. The 2020 market value predicted for the $TiCl_4$ industry is US$ 8 614.7 million and is expected to reach US$ 11 450 million by 2026 (InForGrowth, 2019). The cost of $TiCl_4$ varies depending on the source, quality and quantity. The average cost for purchasing bulk $TiCl_4$ (thousands of tonnes) extends between US$ 950 - 1 300/t. Labs that purchase smaller quantities (in kilograms) can pay as much as US$ 5/kg or US$ 5 000/t (Tronox, 2020). The cost for $TiCl_4$ is therefore in the range of US$ 0.95 - 5/kg or at the 2019 exchange rate of R 14.5/US$ (Nedbank, 2019) the cost range is R 13.8 - 72.5/kg.

6.3. Where is South Africa now?

Similar to titanium mining and upgrading (stage 1 & 2 of the titanium metal value chain), $TiCl_4$ production is also driven by the titanium pigment industry. South Africa does not produce $TiCl_4$ locally but only imports small quantities for research purposes. No $TiCl_4$ import or export data is available from the "Quantec Easy Data" (used for import and export of titanium metal products), and only data on pigment imports was obtained (QuantecEasyData, 2019).

6.3.1. Market (Where is South Africa now?)

Locally there is no $TiCl_4$ market as South Africa no longer has a titanium pigment production plant (closed in 2016). It should be noted that the Huntsman Tioxide South Africa manufacturing facility that closed in 2016 used the sulphate route and not the chloride route for pigment production, thus the plant did not produce or import $TiCl_4$.

QuantecEasyData (2019) reported that South Africa imported 30 374 t of "*pigments and preparations based on titanium dioxide*" in 2018. In the same year the exports were 1 472 t, making the local consumption 28 903 t, as no pigment was produced locally. This means that although there is no local pigment production from $TiCl_4$, there is still a pigment market (based on 28 903 t of local consumption). The gap within the local titanium value chain becomes evident in this section. Titanium mineral concentrates are mined locally, upgraded locally and then exported. A value-added pigment is then imported. This local value chain gap can be closed by either applying the sulphate route for direct pigment production (eliminating the potential for titanium metal production) or the chloride route for $TiCl_4$ production and then producing pigment from the $TiCl_4$.

6.3.2. Product (Where is South Africa now?)

South Africa is not producing $TiCl_4$ but importing small quantities for R&D purposes related to sponge and titanium metal powder production.

6.3.3. Technology (Where is South Africa now?)

South Africa does not have the technology to produce $TiCl_4$ on a commercial scale.

6.3.4. Research and Development (Where is South Africa now?)

The DSI has been driving a beneficiation program that promotes titanium based R&D on titanium feedstock, slag production and various aspects of chlorination of the titanium feedstock. For chlorination an organisation in South Africa built a pilot scale fluidised bed chlorinator and research is ongoing. The feedstock for chlorination under investigation includes titanium slag, upgraded slag, natural rutile, synthetic rutile and ilmenite (Kale and Bisaka, 2016). Technology to produce $TiCl_4$ through chlorination is available from international companies, but this technology is closely guarded and expensive. The interviewees were concerned about the effect the additional consumption on chlorine will have on the existing market and therefore indicated the need for a local market study on the availability of chlorine.

6.3.5. Resources (Where is South Africa now?)

South Africa has access to the major resources needed to establish a local $TiCl_4$ production plant. The country has access to the mineral feedstock, chlorine and petroleum coke.

Titanium feedstock (titanium slag, upgraded slag, natural rutile, synthetic rutile or ilmenite) is readily available in South Africa. Additional resources needed for chlorination are carbon in the form of petroleum coke as well as chlorine. Petroleum coke can be sourced locally from the petrochemical industry, but the use of coke is increasingly being substituted by other means of heating.

The leading chlorine manufacturing companies in South Africa are Sasol Polymers, NCP Chlorochem and Mondi. None of these companies produce $TiCl_4$ and therefore the chlorine is used for alternative industries. Table 17 is a summary of these three companies with their capacities, technology and the main products produced.

Table 17. Chlor-alkali industry of South Africa. (Adapted from: C11 Chlor-alkali, 2010).

Chlor-Alkali producers in South Africa			
Company	Sasol Polymers	NCP Chlorochem	Mondi
Capacity (tpa)	±120 000	±90 000 to 170 000	±15 000
Location	Sasolburg	Kempton Park	Richards Bay
Technology	Membrane/ diaphragm	Membrane	Membrane
Use	PVC, HCl, CsCl2, Hypochloride	Water treatment, HCl, Hypochloride	Paper production
Comment		SA's leading supplier of liquefied packed chlorine	

South Africa also produces chlorine for other African countries indicating that there is a surplus of chlor-alkali products produced locally. The human capital that has been built in this established chlor-alkali industry could be a future resource for the $TiCl_4$ industry.

.

6.4. Vision Element: Where does South Africa want to go?

The vision element for local $TiCl_4$ production is to have access to chlorination technology by 2030 and to have acquired a big enough market for pigment and metal production (local and Africa) for a local plant to be economically feasible.

The majority of the industry experts (89 %) that took part in the survey, agreed with this vision element for local $TiCl_4$ production. Local experts indicated the preferred technology for local $TiCl_4$ production should be imported and that it will not be from local R&D. Disagreements on the vision element indicated that historical studies done on local pigment production concluded that this is not commercially viable in South Africa. In addition to there not being a market for pigment the concern was raised that the quality of titanium alloy powder (remaining market after pigment) would not be achieved at a competitive level in industry. Without a pigment or a metal market there will be no need for $TiCl_4$ production within the next 10 years.

6.5. How will South Africa get there?

The production of $TiCl_4$ is the intermediate step to produce both titanium pigment (chloride route) as well as titanium metal. The development of this capability locally is a crucial step if any one of the two mentioned industries is to be pursued locally.

Most of the interviewees (±70 %) indicated that South Africa should not have a chlorination plant (to produce $TiCl_4$) within the next three years. This vision element changed for the following seven years as approximately 90 % or the interviewees indicated that South Africa should produce $TiCl_4$ by this time. Reasons provided by interviewees for South Africa not to produce $TiCl_4$ locally over short and/or long-term are given below. The long-term reasons represent the comments made by interviewees (the 10 %) that stated that this stage of the value chain should not be developed during the next decade. The reasons for short and long-term were combined as they overlap.

- No $TiCl_4$ production anticipated in South Africa due to lack of formal commitment from government as well as potential commercial partners.
- The local market for $TiCl_4$ is too small.
- South Africa will not be able to compete with the existing $TiCl_4$ markets. This market is dominated by the pigment industry as $TiCl_4$ is a precursor for TiO_2 (pigment) production. China is in the process of improving $TiCl_4$ production (chloride route) and is expected to dominate the market in the near future.

The reasons for South Africa to produce $TiCl_4$ locally over the long-term as stated by interviewees are given below.

- The successful development of a local primary powder production process would create a market for a small $TiCl_4$ plant specifically for titanium powder production not for pigment.
- Technology will have to be sourced externally.
- Growth within the pigment industry will be creating a demand in $TiCl_4$.
- Build a chlorination plant with the main aim to supply the pigment industry. A pigment plant using the chloride route would allow for $TiCl_4$ development (e.g. Human Capital Development (HCD)) and growth of the general titanium industry. Having such a plant would bring the country closer to the potential development of titanium metal.
- The advancement and enhancement of local $TiCl_4$ chlorination research.

It should be noted that not all of the reasons provided by interviewees are seen as valid reasons to include $TiCl_4$ production to the local titanium value chain.

6.5.1. Market (How will South Africa get there?)

The $TiCl_4$ market is driven by the consumption thereof in the titanium pigment industry, which is expected to grow with 8.7% from 2019 to 2025. The main consumers to drive this growth have been identified as printing inks, rubber, chemical fibres, residential and non-residential construction projects (Grand View Research, 2019). The production of titanium metal has a smaller effect and this industry is driven through growth within the aerospace, defence and chemical industries (Market Reports, 2019).

According to an interviewee, chlorination plants (to produce $TiCl_4$) are available for purchase off-the-shelf, but for the plant to be profitable along the economic cycle the plant needs to produce 100 kt of $TiCl_4$ per annum. China does not build a chlorination plant of less than 300 kt per annum and globally they are the main competition. From a molecular point of view 1 mole of $TiCl_4$ gives 1 mole of TiO_2. Therefore, on a mass basis, 190 g/mole gives 80 g/mole or, about 120 kt $TiCl_4$ is required for 50 kt TiO_2. Applying this to South Africa's TiO_2 usage (30 374 t, which includes exports), South Africa would require approximately 73 kt of $TiCl_4$. If a 100 kt $TiCl_4$ plant was to be built a surplus of approximately 27 kt $TiCl_4$ would be produced. This means a market for the hazardous $TiCl_4$ needs to be obtained or an additional market for 11 291 t of TiO_2 needs to be established. Based on these figures South Africa does not have a big enough local pigment market to justify a $TiCl_4$ plant of its own.

As per the 10 year vision element (2030), if an international company does decide to set up a $TiCl_4$ plant in South Africa the following markets could be developed to consume the surplus product: $TiCl_4$ for the manufacturing of catalysts, $TiCl_4$ as a glass and metal surface treatment, titanium dioxide (pigment), titanium metal, water purification and smoke screens. Interviewees indicate that the most likely partnership would be with an existing international company that already has global influence in the $TiCl_4$ market. According to interviewees a similar effort from a local company would not have the required market access. Interviewees also indicated that the most sensible approach by international companies would be to first construct one of two 50 ktpa $TiCl_4$ lines and run it, while building an additional line. A final market related statement given by the interviewees was to focus on the local as well as African markets as this would be the easiest market entry point for a South African $TiCl_4$ supply within a highly competitive industry.

When considering $TiCl_4$ used in the titanium metal industry the demand is driven through growth within the aerospace, defence and chemical industries (Market Reports, 2019).

6.5.2. Product (How will South Africa get there?)

The data collected in this study indicated that South Africa currently does not have a big enough market to produce $TiCl_4$. To be able to reach the 10 year vision element of having a local $TiCl_4$ plant, additional uses (other than for pigment) should be found. $TiCl_4$ can also be used to produce titanium metal, smoke screens (white smoke) for military use, in the manufacture of iridescent glass, as a coagulant for water treatment and as a polymerisation catalyst (Zhao *et al*., 2014).

6.5.3. Technology (How will South Africa get there?)

Two technology routes were identified by interviewees. The first is the commercialisation of the South African chlorination R&D project (fluidised bed pilot plant) and the second to import an existing technology. The first option will be discussed in more detail under the R&D section. Interviewees indicated that a more feasible option to establish chlorination technology locally, is for government to consider approaching a holder of established chlorination technology. The benefit to the technology holder should be in the form of certain incentives to make the technology feasible.

6.5.4. Research and Development (How will South Africa get there?)

South Africa should continue the research on $TiCl_4$ production through the fluidised bed chlorination process. According to the interviewees no techno-economic assessment has been done on the local $TiCl_4$ production research. Obtaining the economic feasibility of this process could be highly beneficial to motivate additional resources to continue the research. Interviewees stated that future research on the chlorination process will look at the re-design of the reactor (change of heat source) and the upscaling of the process.

R&D driven projects should be designed to create a market for the $TiCl_4$ industry vision element to be developed by 2030 (e.g. a market study for $TiCl_4$ consumption). This market should be built based on the production of a feasible $TiCl_4$ production plant. As per interviewees historical studies indicated that a local pigment plant would not be commercially viable. This statement should be revised from a 2020 and a 2030 position and the revision should include techno-economics on local pigment production. A smaller secondary market should also be developed, and this could be driven by $TiCl_4$ as feedstock for local titanium metal powder production (as per the 2030 titanium powder production vision element to be discussed in Section 10.4). Although the establishment of a pigment market would be the deciding factor for the construction of a 100 ktpa plant the $TiCl_4$ market to produce titanium metal powder was the main focus of this study and would be subordinate to pigment production. If a market growth driven by the need to consume the surplus $TiCl_4$ in this industry cannot be predicted, then $TiCl_4$ production should not be considered for the 10 year roadmap.

Environmental research in the form of an Environmental Impact Assessment (EIA) should be conducted in conjunction to the process development. The hazardous chemicals involved in production of $TiCl_4$ have been identified by Market Reports (2019) as a direct obstacle for the growth of the $TiCl_4$ industry. This has especially been observed in stringent government regulations being applied in Europe and North America. An opinion from the interviewees, however, did not see the production of $TiCl_4$ as an environmental concern as South Africa already has expertise working with chlorine and stated that $TiCl_4$ is easier to handle than chlorine.

6.5.5. Resources (How will South Africa get there?)

South Africa has access to the required raw materials to sustain the development of a $TiCl_4$ plant (titanium mineral feedstock, chlorine and petroleum coke). South Africa exports some of its produced chlorine to African countries, therefore a surplus of chlorine is available to produce $TiCl_4$ if the economics justifies it.

As outlined in section 6.5.1. South Africa has an established chlor-alkali industry with expertise that can be applied in the $TiCl_4$ field. Interviewees expressed the opinion that working with $TiCl_4$ is easier than working with chlorine and these skills are already developed locally. The continued research in this stage of the titanium metal value chain would also aid in the establishment of human capital within the field and allow for more individuals to be trained in order to create an experienced pool of people.

6.6. Discussion: Roadmap for $TiCl_4$ Production

South Africa does not produce $TiCl_4$ locally and therefore stage 3 is the first missing fragment of the local titanium metal value chain. Globally the biggest market for $TiCl_4$ production is to feed into the pigment industry (90 %). South Africa does not have a big enough pigment industry to justify a $TiCl_4$ plant. South Africa also does not have access to the required technology.

Although no $TiCl_4$ is currently being produced in South Africa, this is one of the value chain stages recommended to be established in the next decade. Chapter 6 was compiled as an answer to the roadmapping questions on “Where is South Africa now?”, “Where does South Africa want to go?” and “How will South Africa get there?” when considering local $TiCl_4$ production. Table 18 is a summary obtained from answers to these questions.

Table 18. Summary of $TiCl_4$ production (stage 3).

Where is SA now?	Market	• Import limited amounts for local R&D
	Product	• None
	Technology	• None
	R&D	• Chlorination of titanium feedstock (fluidised bed technology) • Market study on local chlorine availability
	Resources	• Mineral feedstock: rutile, ilmenite and slag • Other resources: Chlorine and petroleum coke • Skills from existing local chlorination industry • Relatively cheap electricity compared to first world countries
Where does SA want to go?	Vision element	*The vision element for local $TiCl_4$ production is to have access to chlorination technology by 2030 and to have acquired a big enough market for pigment and metal production (local and Africa) for a local plant to be economically feasible*
How will SA get there?	Market	• Set up of a $TiCl_4$ plant: • Driven by the titanium pigment industry but also used as feedstock for titanium metal powder production • Use locally produced $TiCl_4$ as feedstock to produce pigment, titanium metal and other products • Enter the local and African pigment market via (chloride route)
	Product	• In addition to the main consumer (proposed local pigment industry), additional uses for the surplus $TiCl_4$ needs to be found, potential $TiCl_4$ uptakes: ○ titanium metal production, ○ smoke screens (white smoke) for military use, ○ in the manufacture of iridescent glass, ○ as a coagulant for water treatment, and ○ as a polymerisation catalyst
	Technology	• Option A: Import existing technology (100 ktpa plant) • Option B: Commercialisation of local fluidised bed technology
	R&D	• Research on fluidised bed chlorination process • Techno-economic assessment on fluidised bed chlorination process • Market study to find takers for surplus $TiCl_4$ from 100 ktpa plant • Techno-economics on feasibility of local pigment production • Environmental research (EIA) to ensure stringent government regulations are being met
	Resources	• Sufficient raw material to develop a $TiCl_4$ industry: titanium mineral feedstock, petroleum coke and chlorine • Skills from existing chlorination industry • Skills from chlorination R&D • Relatively cheap electricity & an increase in renewable energy

The data displayed in Table 18 was obtained from both primary and secondary sources. The layout of the table follows the generic technology roadmap layout that allows this data to be projected onto a 10 year roadmap for the local titanium metal industry's stage 3 of the value chain, $TiCl_4$ production. This roadmap can be observed in Figure 27.

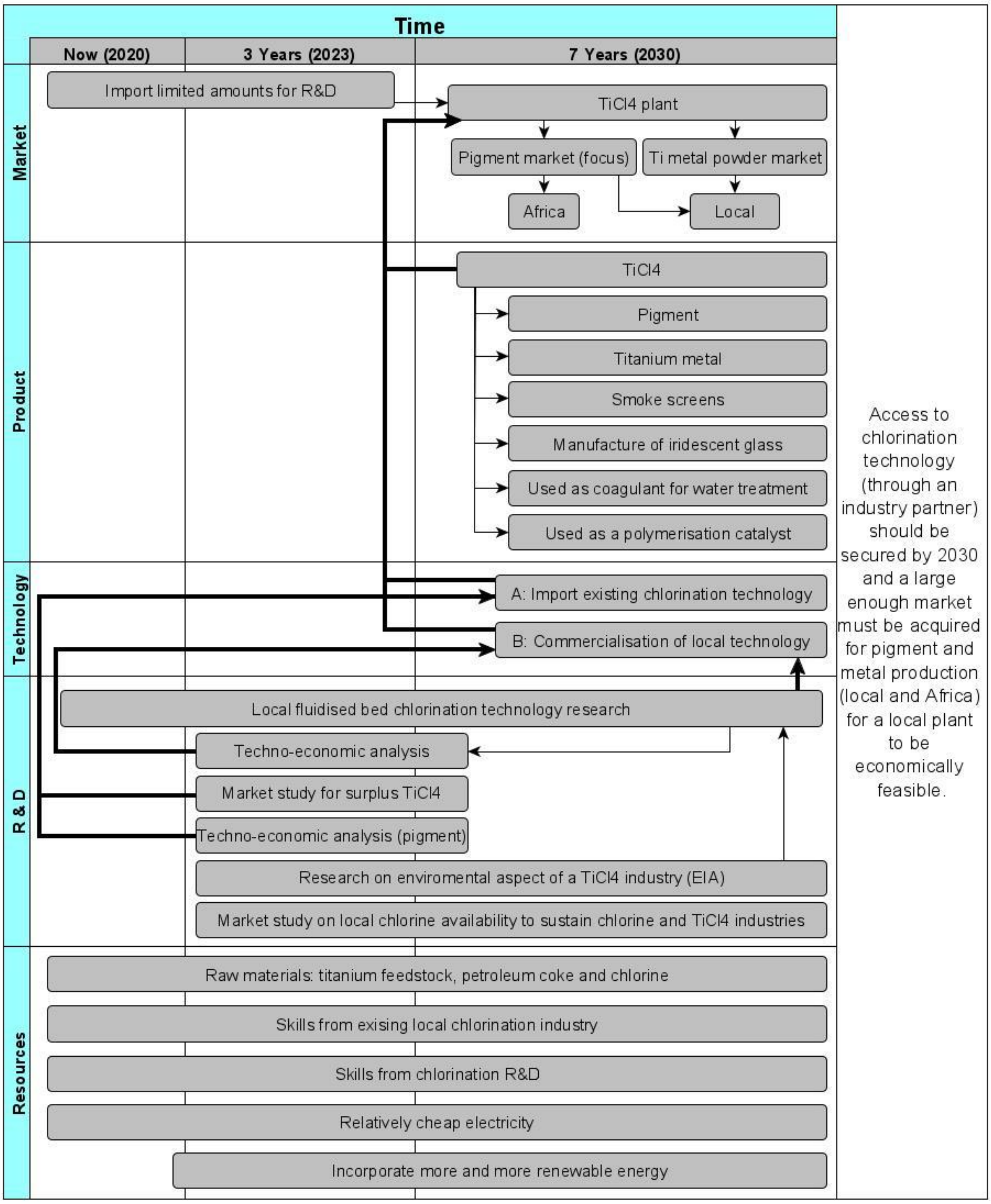


Figure 27. The local 10 year roadmap for $TiCl_4$ production (stage 3).

Currently the market for $TiCl_4$ in South Africa is limited to the liquid being imported for R&D purposes. The results generated from this study indicate that this stage of the value chain should be expanded within the next decade by establishing local $TiCl_4$ production. In the technology paragraph, two different technology routes will be discussed in more detail, but as indicated by the thick arrows in Figure 27 the technology will have a direct influence on the market. If South Africa decides to acquire a 100 ktpa $TiCl_4$ production plant (technology option A), this plant's main market would be the pigment industry (for South Africa as well as Africa) with a smaller portion distributed to the titanium metal industry. Alternatively, if economically viable, South Africa can build a $TiCl_4$ plant using locally developed technology (technology option B) allowing for lower quantities of $TiCl_4$ production as feed only for titanium metal production in South Africa. The possibility of this $TiCl_4$ being used for pigment production has not been out ruled. This is dependent on the techno economic analysis of the plant in addition to the plant size (which has not yet been determined) and therefore pigment production form local $TiCl_4$ technology has been excluded.

Locally the pigment market is not big enough to consume the proposed 100 ktpa $TiCl_4$ production. For this reason, South Africa would have to include the African market as well as consider other products that can be produced from the surplus $TiCl_4$ produced by the plant (within the seven year roadmapping period 2023-2030). Options of products to be produced from $TiCl_4$ are pigment, titanium metal, smoke screens (white smoke for military use), the manufacturing of iridescent glass, the use of $TiCl_4$ as a coagulant for water treatment, and the use of $TiCl_4$ as a polymerisation catalyst.

For South Africa to localise $TiCl_4$ production by 2030 the two best options are to commercialise the local fluidised bed technology still under R&D or to import existing chlorination technology. The local R&D on fluidised bed chlorination technology will be discussed in the R&D paragraph. Globally the production of $TiCl_4$ utilises a mature technology that is expensive and protected. The results collected from this study indicate that this technology would be accessible through international industrial partnerships and government intervention through incentives.

The local R&D on fluidised bed chlorination technology has produced a pilot scale chlorination plant. This research should be pursued for the next decade or until a decision is made on its economic viability. From the results no techno-economics has yet to be conducted on this technology and the need for such a study was highlighted. Interviewees also highlighted the link between this stage of the value chain and the already existing chlorine industry in South Africa. Experts indicated the need for R&D to investigate the chlorine availability in South Africa to sustain the existing chlorine as well as the proposed $TiCl_4$ industry. This should be conducted in conjunction with environmental research on the impacts of developing a $TICl_4$ industry locally considering both technology options. For South Africa to decide on the import of existing chlorination technology, a techno-economic assessment should be conducted (within the next three years) to investigate the feasibility of establishing a pigment plant in the country. It was already stated that the local pigment industry would not be able to consume all of the $TiCl_4$ produced. This means that a need also exists for South Africa to conduct a market study to find takers for the surplus $TiCl_4$.

The availability of resources is not a limiting factor for the establishment of this stage of the titanium metal value chain. South Africa has sufficient raw materials such as titanium feedstock, petroleum coke and chlorine (to be confirmed though R&D) to sustain a 100 ktpa $TiCl_4$ plant. In addition to the available raw materials South Africa has an existing workforce with experience in the chlorination industry. The results collected for this study indicated that skills and experience should be easily transferable between the two industries. Lastly, South Africa is considered to have relatively cheap electricity compared to first world countries (see Figure 23). South Africa is also committed to incorporating more and more renewable energy into its energy mix. This will not only reduce the country's carbon footprint but also ensure a more stable energy platform as companies are able to generate their own electricity.

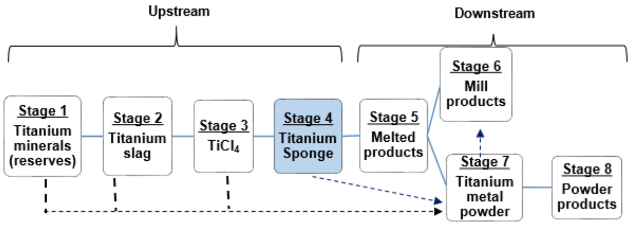
6.7. Chapter Summary

Chapter 6 provided a contextual background on $TiCl_4$.The chapter started out with a literature review on how $TiCl_4$ is produced as well as the environmental risks associated with this this stage of the titanium metal value chain. Globally the market for $TiCl_4$ trade is dominated by four countries namely the USA, Japan, China and Russia and the bulk of the $TiCl_4$ produced in these countries supplied as feedstock to the pigment industry.

South Africa does not have a $TiCl_4$ market, but the results presented in Chapter 6 indicates that this should change within the next decade. The local production of $TiCl_4$ has been identified as one of only two value chain stages that should be developed locally within the next 10 years. As the main market for $TiCl_4$ is not the titanium metal industry, the establishment of this stage would be dependent on the main market driver which is titanium pigment and should therefore be accompanied by a pigment plant.

The results presented in this chapter state that a potentially route for establishing $TiCl_4$ production locally is though importing existing chlorination technology though a commercial partnership. This technology recommended for the plant should be able to produce 100 ktpa $TiCl_4$ for it to be economically viable. This size plant would create a surplus $TiCl_4$ supply locally even if a pigment plant was set up to produce pigment for the local demand. The solution presented in this study is to find alternative industries that could make use of the additional $TiCl_4$ expected to be produced by the plant. These alternative industries could include the production of titanium metal, smoke screens, the manufacturing of iridescent glass, the use of $TiCl_4$ in water purification as well as, the use of $TiCl_4$ as a polymerisation catalyst.

7. Chapter 7: Stage 4 (Titanium Sponge)



7.1. Literature Review

The production of titanium sponge is the main method used globally for titanium metal production. This chapter will elaborate on the available literature on processes used to produce titanium sponge which are the Kroll and Hunter processes. Literature on the global outlook for sponge production will also be discussed together with market information.

7.1.1. Sponge Production

Titanium sponge is a crude form of titanium metal. It is called “sponge” due to its sponge-like appearance. The common methods to produce titanium metal are the Kroll process, the Hunter process and the fused salt electrolysis process. Out of these three the Kroll process produces ±99 % of the global titanium metal (Nagesh, Ramachandran and Subramanyam, 2008).

Different grades of titanium sponge exist with the main grades having a titanium content between 99.2 % and 99.8 % and the lowest grades having a minimum titanium content of 97 % (Roskill reports, 2013). The grade of sponge determines its application and therefore only the higher grades of sponge are suitable for the application in the aerospace industry. Rotor or premium grade sponge is the highest grade sponge and used in aeroplane engines (Roskill reports, 2013). Companies that want to produce rotor grade sponge must apply extremely strict quality control in both the production and crushing phase of sponge production. These companies also have to apply vacuum distillation to remove the magnesium and magnesium chloride residues introduced during the Kroll process (while the sponge remains under vacuum) (Roskill reports, 2013).

As with $TiCl_4$ production the grade of sponge produced is dependent on the quality of the original raw material (rutile, synthetic rutile or slag). Although there are processes available to refine and upgrade titanium, some contaminants (such as nitrides and carbides) are not removed and this results in areas of weakness within the final product (Roskill reports, 2013).

Except for the quality of the $TiCl_4$ additional contamination, such as chromium and nickel from the stainless steel vessels (such as in the Kroll process) can occur. To decrease this effect the sponge in the centre of the pool is assumed to be have less contaminants and is usually the selected fragment for melting to produce rotor grade metal. The sides of ends of the sponge are cut off and are usually used to produce metal for industrial applications or as off-specification metal in ferrotitanium (Roskill reports, 2013).

7.1.2. The Kroll Process (Magnesium Reduction of $TiCl_4$)

The Kroll process is dominating global sponge production. It was developed in the 1930s by Wilhelm Kroll with the first commercial production in 1946 (Roskill reports, 2013). The Kroll process is the magnesiothermic reduction of purified $TiCl_4$ in a stainless steel reactor under a positive argon gas pressure. The Kroll process is a batch process (Nagesh, Ramachandran and Subramanyam, 2008). The Kroll process can be broken down into three main steps displayed in Figure 28.

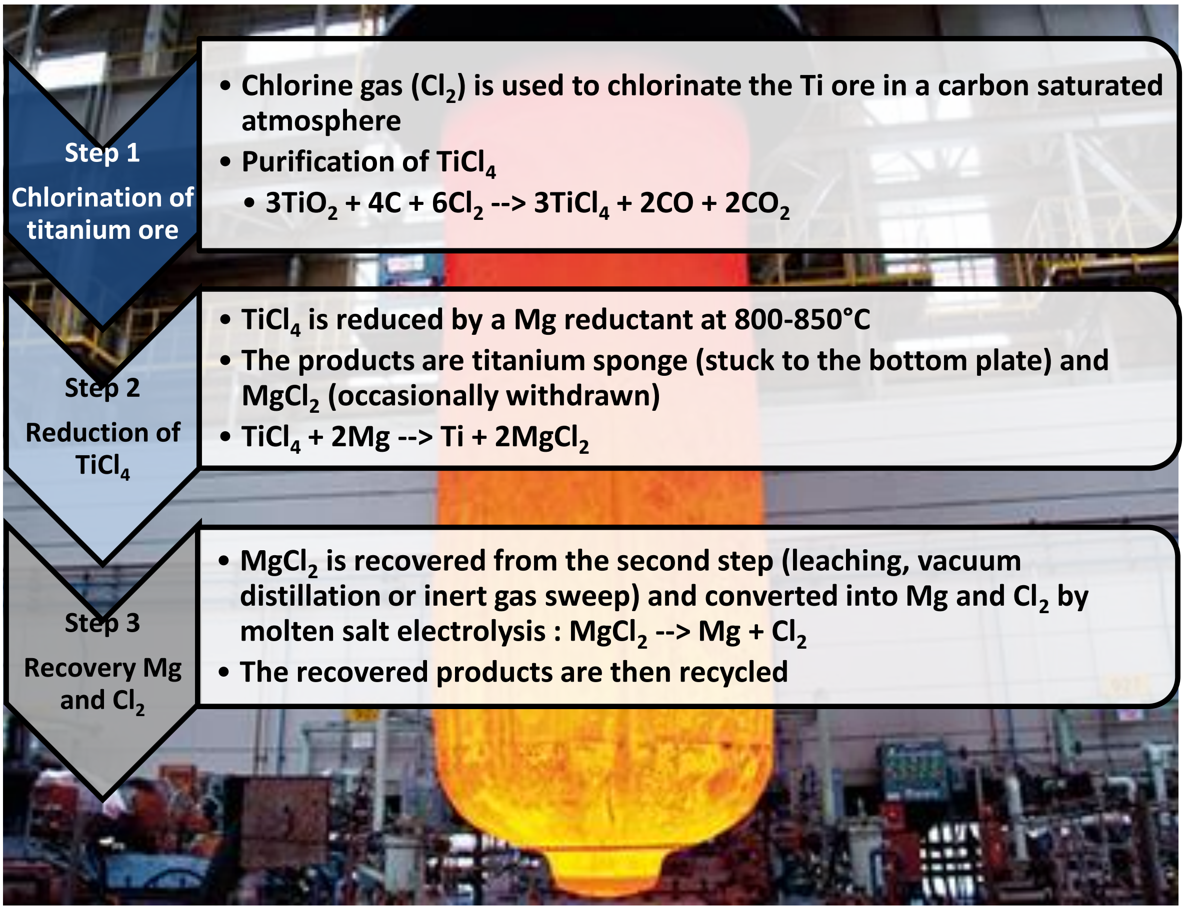


Figure 28. The Kroll process (Adapted from: Nagesh, Ramachandran and Subramanyam, 2008; Bordbar, Yousefi and Abedini, 2017; OSAKA Technologies, 2018).

Over time, the Kroll process has evolved and grown to become the dominating and preferred titanium production method. Recent advancement include combining the reduction and vacuum distillation (preferred $MgCl_2$ recovery step) stations, enlarging the batch size, computerising the process for better control and improved quality evaluation (Nagesh, Ramachandran and Subramanyam, 2008).

Even with all the improvements, there remains some negative aspects of using this process. The main restraint is that the Kroll process is a batch process. The Kroll process also results in iron contamination of the outer edge of the sponge. During the formation of the sponge some chlorine wastes, such as iron chlorides, are also captured in the sponge and reduces its quality. Thus the sponge that is created is not of uniform quality, but can be improved with further processing (Bordbar, Yousefi and Abedini, 2017). These challenges result in continuous research into titanium production to find a cheaper alternative for titanium metal production. Several countries are exploring numerous methods to find a technology that could replace the Kroll process. None of these countries have reported significant success.

7.1.3. The Hunter Process (Sodium Reduction of $TiCl_4$)

In 1910, Mathew A. Hunter was the first to isolate high purity titanium metal by the reduction of $TiCl_4$ with sodium (Roskill reports, 2013). At the time, this process was designed to produce an improved quality sponge (compared to the Kroll process) with the aim to service the aerospace industry. The Hunter process did produce commercially significant titanium between the early 1950s and the early 1990s, but advances of the Kroll process caused the economic viability of the Hunter process to drop significantly, leaving the Kroll process to become the industrial standard once again (Nagesh, Ramachandran and Subramanyam, 2008; Roskill reports, 2013). According to Roskill (2013) one of the only operating plants utilising the Hunter process is the Honeywell plant in the USA. The main steps from the Hunter process are displayed in the flow diagram in Figure 29.

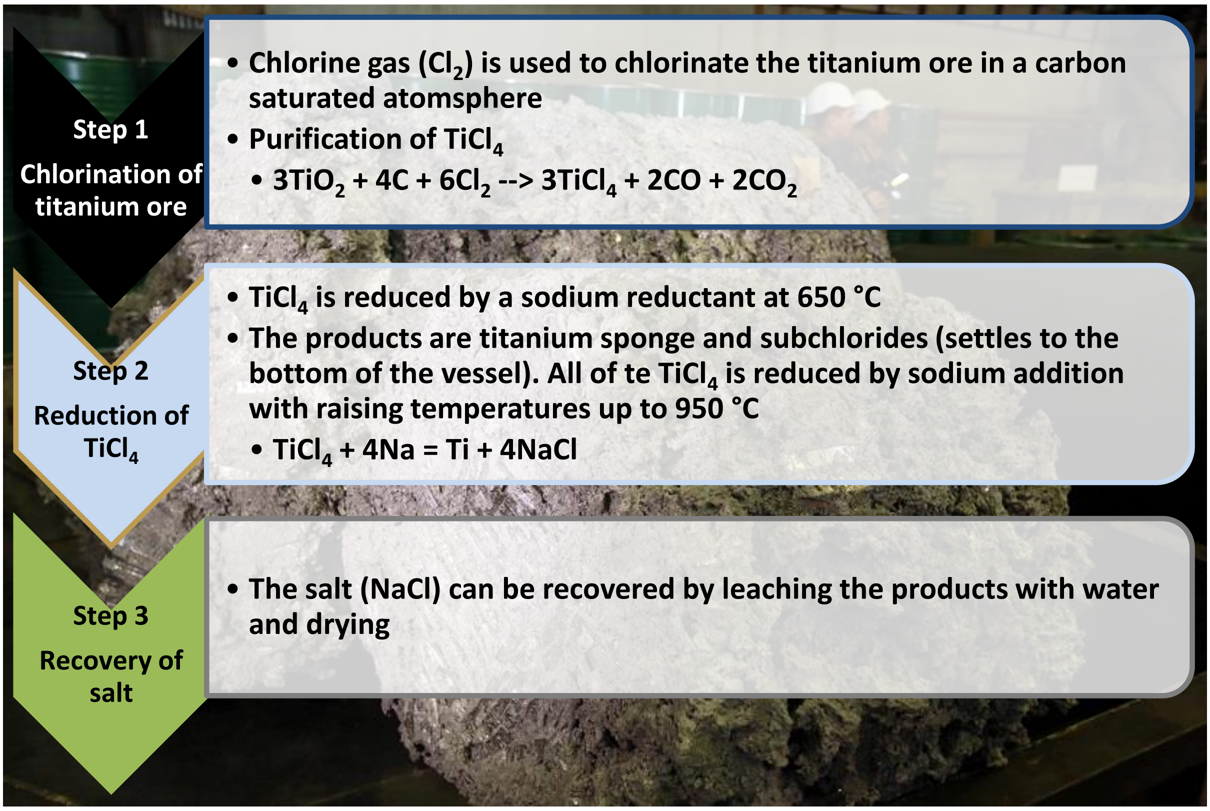


Figure 29. The Hunter process (sodium reduction of $TiCl_4$) (Source: Roskill, 2013; DF, 2015).

It is widely known that the production of titanium metal through the Kroll and Hunter batch processes is expensive. When producing Kroll sponge this process accounts for almost 40 % of the final mill product cost (Jackson, 2007). Except for this expensive upstream sponge production part, further processing the titanium metal to a useable product is also expensive (applying the conventional wrought titanium approach).

Ongoing research to reduce the cost of production and processing (machining and fabrication) can be observed on a global scale. When considering sponge producing batch processes (Kroll and Hunter) research seems to have reached a plateau, with the Kroll process being the most economic process. The combination of the two financial drawbacks mentioned in the paragraph above (sponge production followed by conventional wrought titanium approach) are the primary motivation for R&D within powder metallurgy (PM) of titanium (Fang *et al*., 2017).

7.2. Global Outlook: Titanium Sponge

Titanium sponge is the main feedstock to produce downstream titanium metal products. In industry the use of sponge is also substituted with the recycling of titanium scrap and as a result the price trends are interlinked. In 2019 the global scrap usage for downstream applications was 29 % compared to the 71 % of sponge (Roskill, 2019).

In 2019 there was an oversupply of titanium sponge and the utilisation rate quoted by Roskill (2019) was 70 % as the capacity was 318 ktpa and the output was only 223.2kt of which approximately half was premium grade. The bulk of the sponge is produced in China, Japan and Russia. Globally there are 25 sponge producing companies and a total of 27 sponge production plants. After the production of titanium sponge only a fraction of it is traded as most of the plants also incorporated downstream melting capacity (Roskill, 2019). The world capacity for titanium sponge production (per country) for 2000 - 2019 is displayed in Figure 30.

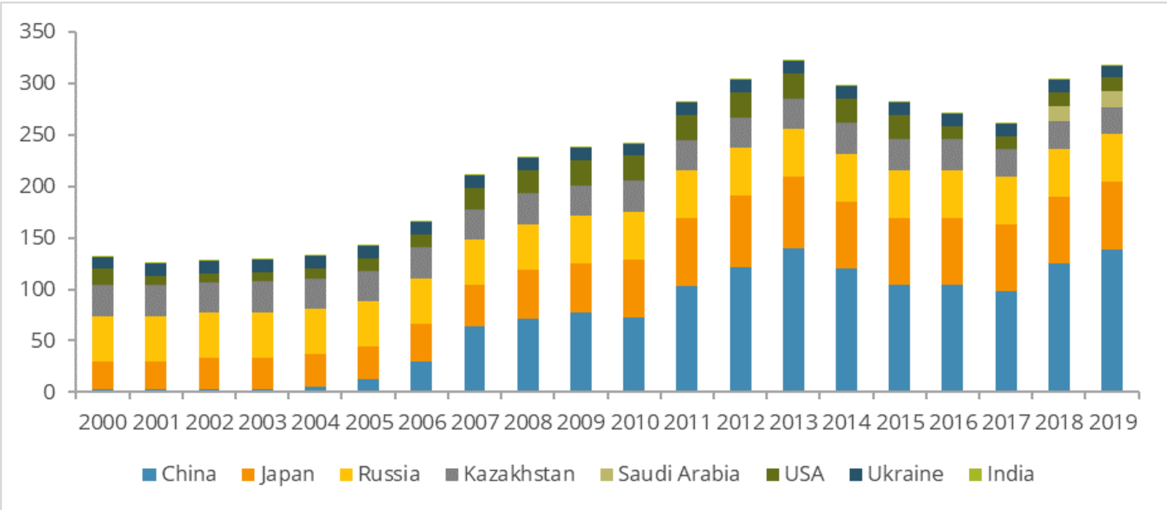


Figure 30. World capacity for titanium sponge by country (ktpa) (Source: Roskill, 2019).

From Figure 30, sponge production capacity in China has grown significantly since 2005. This led to an oversupply in the market resulting in plant idling and closures affecting China and America during 2013 - 2014 (Roskill, 2019). Additional plant closures followed in China in 2017 - 2018, due to environmental issues with the plants. However, China built additional capacity and new plants were also commissioned during this period ensuing that China had the biggest production capacity globally. Most of the sponge and scrap produced in China gets consumed in China (Roskill, 2019).

According to Roskill (2019) the majority (64 %) of sponge produced is industrial grade and therefore non-aerospace sponge. Only four countries are able to produce aerospace grade sponge, and these are Japan, Russia, Kazakhstan and the USA. The high-grade sponge producing capacities of the mentioned plants were estimated by Roskill (2019) as 131 ktpa. High-grade implies that less contaminants are included in the sponge and therefore the titanium content is larger. From this 70 % of the sponge is expected to be suitable for the use in aerospace application (the remaining 30 % is of a lower grade due to the production process). Roskill (2019) also reports that the available capacity of aerospace grade sponge should be calculated on an 85% operating rate and therefore the availability of aerospace grade sponge comes down to 111 ktpa.

The trade in titanium sponge has been inconsistent for the last 10 years. The global export market for titanium sponge peaked in 2012 with more than 60 kt of sponge being exported. Since then the market took a dip and only recovered in 2017. Currently the global sponge export market is making a recovery with the forecast for 2019 being 52 kt. The main exporters of titanium sponge are Japan (± 60 %), Kazakhstan (±23 %), and Russia (±13 %). Japan’s exports are dominantly aerospace-grade sponge and the export destination is mainly the USA with lesser amounts going to the UK (Roskill, 2019). Sponge exports from Kazakhstan and Russia are dominated by low-grade titanium sponge but both countries also export high-grade sponge (26 % and 17 % respectively). This is important to note because it indicates that more than 70 % of the sponge exports are of aerospace grade.

It should be noted that from the Roskill 2019 report the latest figures (expected for 2019) on sponge production in China was 82 kt of titanium sponge. The expected sponge exports for the same year was 868 t indicating that China expected to use approximately 98 % of the sponge produced locally for 2019. In addition, China imports approximately ±6 kt of sponge annually (Roskill, 2019).

The largest importer of titanium sponge is the USA with more than 50 % of the global import trade going to the USA. The second largest importer of titanium sponge is the Netherlands followed by China. Roskill (2019) anticipated that sponge production would increase at a rate of around 1.9 % per year from 2019. The report also predicts that the growth for premium grade sponge should be higher as there are fewer qualified producers.

In the second quarter of 2019 the US reported titanium sponge import prices of US$ 10.11/kg. Unfortunately, the Roskill report does not distinguish between the cost for high-grade and low-grade sponge. The report does mention that the US cost sometimes differ with approximately US$ 2/kg compared to the domestic Chinese cost and states that this might be contributed to the US mainly importing high-grade sponge mostly from Japan.

7.3. Where is South Africa now?

South Africa is not producing titanium sponge. The country is not involved in the import or export of stage 4 of the titanium metal value chain.

7.3.1. Market (Where is South Africa now?)

There is no market for titanium sponge in South Africa as the country does not have melting facilities to further process the sponge. Globally there is an oversupply of titanium sponge, thus the market is saturated. The latest price for titanium sponge imports into the USA is US$ 10 - 11/kg, therefore if South Africa wants to enter the titanium sponge market it must be able to produce and deliver sponge at a similar or cheaper cost. It should also be noted that the bulk of the international sponge trade is in aerospace grade sponge.

7.3.2. Product (Where is South Africa now?)

South Africa does not have a Kroll or Hunter titanium sponge production facility. The product produced from these facilities is titanium sponge.

7.3.3. Technology (Where is South Africa now?)

South Africa does not have sponge production technology. Although this is old and established technology, this plant is expensive and would require a vast amount of capital to construct.

7.3.4. Research and Development (Where is South Africa now?)

Limited research on sponge production has been conducted in South Africa. In 2010 an article was published by Hockaday and Bisaka (2010) that discussed the experimental production of Kroll sponge in a 1 kg titanium sponge batch reactor. The aim of the research was to develop skills and a knowledge base to produce titanium sponge in South Africa.

7.3.5. Resources (Where is South Africa now?)

South Africa does not have the resources needed to produce titanium sponge.

- South Africa is not producing the titanium feedstock which is $TiCl_4$.
- South Africa does not have a magnesium production plant (reduction used in the Kroll process) (Van Vuuren, 2009b).
- Although South Africa has cheap electricity the electricity supply is unreliable.
- South Africa does not have the required skill set to run a sponge facility as the country has never had such a facility. According to Van Vuuren (2009)

there are only a small number of local people with some titanium production experience.

7.4. Vision Element: Where does South Africa want to go?

South Africa does not foresee a sponge production plant within the next 10 years in its overall titanium metal vision.

Although the bulk of the survey answers agreed that South Africa should not be producing titanium sponge within the next decade, two points raised (contrary to the vision element) cannot be ignored.

1. The first point stated that as soon as $TiCl_4$ is locally produced, alternative titanium metal production technologies should be investigated. One such a technology is titanium metal production through titanium oxicarbides, but this process is still under development and this will not be possible within a 10 year framework.
2. The second comment referred to Kerala Minerals and Metals Limited (KMML) in India. This is a small tonnage (200 - 500t) high purity sponge production plant that produces aerospace grade titanium (based on the Kroll process). The point made in the survey indicated that a sponge plant of the appropriate size could be established locally and that this plant would drive innovation and specialist job creation. In addition, it was mentioned that the lack of sufficient magnesium and sodium production in South Africa should be addressed before venturing into large scale sponge production.

Although both these comments were considered, it was concluded that South Africa should not have a titanium sponge production plant established within the next decade. The next section will elaborate on the reasons for excluding titanium sponge production in South Africa for the next 10 years.

7.5. How will South Africa get there?

Based on the data collected from experts in the local titanium field, South Africa is not expected to have a titanium sponge plant in the next 10 years. It should however be noted that the potential for the need for a sponge plant does increase comparing the results from the long-term plan (10 years) to the medium-term plan (three years). Table 19 indicates the sentiment analysis of the titanium industry experts for establishing a sponge plant within the next three and 10 years.

Table 19. Opinion analysis of experts that feel South Africa should not have a sponge plant.

3 Years	10 years
75 % of the answers were negative regarding having a sponge plant in South Africa within the next three years	60 % of the answers were negative regarding having a sponge plant in South Africa within the next 10 years.

Reasons for not having a titanium sponge plant in decreasing order of importance are given below. These reasons were identified during the interview stage of data collection and ranked during the survey stage.

- It is not economically viable to construct a capital-intensive titanium sponge production plant locally as South Africa would not be able to compete with the international market.
- The investment risks in South Africa are too high for industrial partners.
- South Africa is experiencing an electricity supply crisis resulting in electricity constraints.
- The titanium sponge market is over-saturated.
- The precursor for sponge is $TiCl_4$ and South Africa does not produce it.
- The production of sponge is energy inefficient and not environmentally friendly.

7.5.1. Market (How will South Africa get there?)

Although the bulk of the results indicated that South Africa should not invest in a sponge plant, some results indicated that South Africa should consider importing titanium sponge. The recommendation for this was that South Africa establishes trade agreements with countries buying local slag and rutile and then buy sponge back from them at a reduced rate. The processing of titanium sponge (a melting facility) will be discussed in more detail in the next chapter, but for now it should be noted that this is an expensive and complex process.

The benefits of processing imported sponge include the establishment of high-level skills (human capital development) and the production of high value products. By importing the sponge, some of the local environmental concerns will be eliminated. This option is also not dependent on the pigment market as it does not require the local production of $TiCl_4$ (option A in Figure 27). If South Africa imports a high-grade sponge it opens the possibility of the country to access the aerospace market. If South Africa imports a lower grade sponge it would be able to access the lower grade markets such as the chemical industry. In the chemical industry this excludes any products that are produced out of CP grade titanium.

7.5.2. Product (How will South Africa get there?)

As South Africa is not producing titanium sponge, it will not produce products from sponge. This could change if sponge is imported. Importing a high-grade sponge would create the possibility of producing products for the aerospace industry. Importing a low-grade sponge could lead to the production of lower grade products for industries such as the lower grade products used in the chemical industry.

it would be able to access the aerospace market for titanium metal. If South Africa imports a lower grade sponge it would be able to access the lower grade markets such.

7.5.3. Technology (How will South Africa get there?)

If South Africa was to import titanium sponge, a reduced cost will have to be agreed on and this would require government intervention with trade agreements. A melting facility would be required to further process the sponge. Although the import of sponge would require the establishment of downstream processing facilities the benefit of this would be that upstream processing facilities required for stage 3 ($TiCl_4$ production) and stage 4 (sponge production) would not be needed. This option would not be dependent on the establishment of the pigment market that is one of the major considerations for the establishment of stage 3 ($TiCl_4$ production) as this need would be bypassed through importing sponge.

7.5.4. Research and Development (How will South Africa get there?)

Interviewees recommended the possibility of South Africa importing titanium sponge and melting it locally to produce melted products such as ingots, billets and blooms. If South Africa decides to import sponge and establish all the downstream processing facilities locally, then the country should continuously conduct research on establishing the missing phases of the conventional titanium metal value chain. These stages are the production of $TiCl_4$, the production of titanium sponge and the production of melted products.

The production of titanium metal is confined to stage 4 (titanium sponge production) and stage 7 (titanium powder production). This means that if South Africa wants to produce titanium metal one of these two stages would need to be established. The current stance on titanium powder production will be discussed in more detail in Chapter 10, but according to the roadmapping vision element for stage 4 (sponge production), this stage should not be developed within the next decade. Interviewees and the answers from the survey did however indicate that sponge production is an important stage of the titanium metal value chain. The results also indicated that South Africa should continuously monitor the global innovations within this stage of the value chain for the possibility of the technology to become feasible for local application (such as the KMML 500 t sponge facility). Novel titanium metal technologies should also be researched and explored.

7.5.5. Resources (How will South Africa get there?)

No raw material would be needed if the country imports titanium sponge. South Africa has two of Africa's biggest ports. They are located at Durban and Richards Bay. These ports could be used to receive imported sponge to be further processed locally.

7.6. Discussion: Roadmap for Titanium Sponge Production

Considering the titanium sponge vision element for South Africa, no sponge production plant is foreseen to be constructed in the country for the next decade. Globally there is an oversupply of sponge production and considering this together with the absence of $TiCl_4$ feedstock in the country the potential for a sponge production plant within the next decade is low.

Chapter 7 discussed the global and local outlook on titanium sponge production. This global outlook was combined with the opinions from local experts to answer the three roadmapping questions as presented in the methodology section of this research: "Where is South Africa now?", "Where does South Africa want to go?" and "How will South Africa get there?" when considering the potential of producing titanium sponge locally. A summary of these answers is presented in Table 20.

Table 20. Summary of titanium sponge production (stage 4).

Where is SA now?	Market	• None
	Product	• None
	Technology	• None
	R&D	• Limited historic R&D on the production of Kroll sponge
	Resources	• None
Where does SA want to go?	Vision element	*South Africa does not foresee a sponge production plant within the next 10 years in its overall titanium metal vision*
How will SA get there?	Market	• None
	Product	• None
	Technology	• None
	R&D	• Expert interactions indicated that South Africa should explore the possibilities surrounding the import and local processing of titanium sponge • A techno-economic analysis on titanium sponge imports and processing should be conducted in order to determine the feasibility of this possibility • Conduct a case study on India's 500 tpa titanium sponge plant (KMML)
	Resources	• None

Both primary and secondary information collected for stage 4 of the titanium metal value chain (titanium sponge production) indicated that South Africa should not produce titanium sponge within the next decade. Table 20 is structured to follow the generic technology roadmap layout and a projection of this table on the roadmap for this stage is presented in Figure 31.

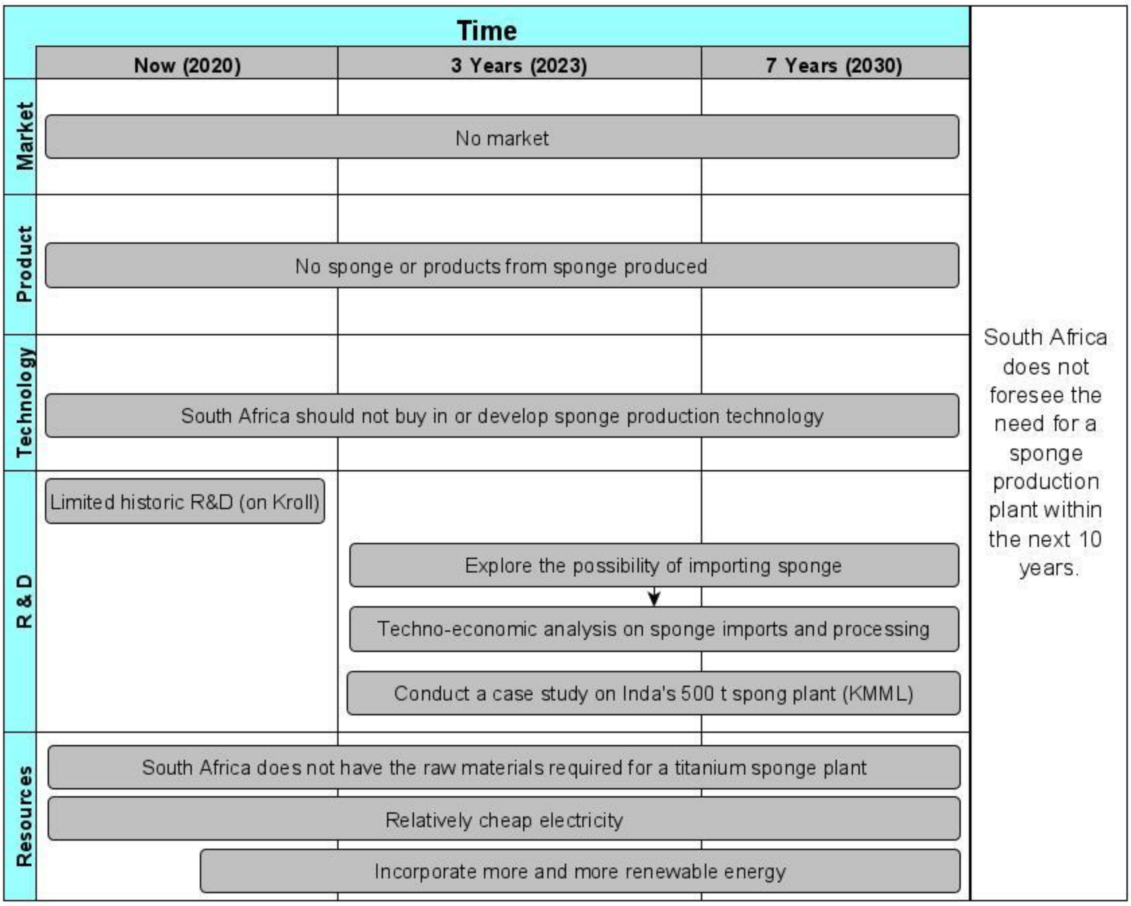


Figure 31. The local 10 year roadmap for titanium sponge production (stage 4).

When considering where South Africa is now, the table indicates that there is no market for titanium sponge, no titanium sponge products, no technology and no resources in South Africa. The only layer that has been populated is R&D which indicates that only limited historic R&D has been conducted on titanium sponge production using the Kroll process.

This stage of the titanium metal value chain is the first stage that this study indicated not to be established within the next decade. This means that by the year 2030 South Africa will still display fragmentation of the titanium metal value chain. As this stage will be absent for the roadmapping period the presented vision element states that “South Africa does not foresee a sponge production plant within the next 10 years”.

The roadmap presented in Figure 31 shows no advances on the development of this stage of the value chain over the next decade (on the x-axis indicating time). The answers for "How will South Africa get there?", with the "there" being the vision element of the value chain stage that should not be developed, does not indicate any efforts of improvement. The only layer that has been populated with future activities is the R&D layer.

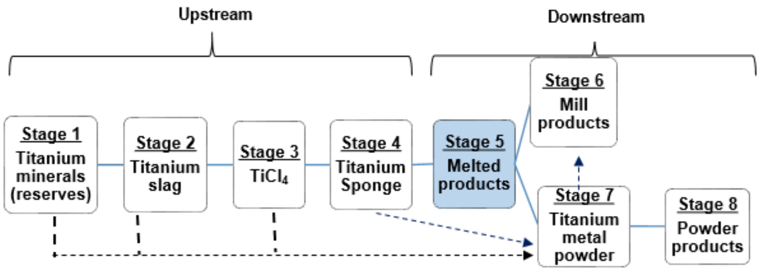
The R&D layer indicates that South Africa should explore the possibility of importing titanium sponge for local processing. This future R&D should be accompanied by a techno-economic study to indicate whether such an effort should be considered as the processing of titanium sponge comes with its own challenges (to be discussed in Chapter 8 and 9). The driver for conducting R&D on titanium sponge import is that sponge could be locally processed to feed into the next stage of the titanium metal value chain (mill product production). Additional R&D that should be conducted is the investigation on the circumstances that made a 500 t titanium sponge plant (KMML) in India feasible (case study analysis). Obtaining more information on the success of this Indian company might be beneficial to the local development of this stage of the titanium metal value chain.

7.7. Chapter Summary

Chapter 7 provided contextual information on titanium sponge. The literature review conducted on this stage of the titanium metal value chain (stage 4) elaborated on the two main methods used for sponge production. The Kroll process has dominated titanium metal production for more than 70 years and is still being successfully implemented in several countries. The global outlook for titanium sponge indicates that there is an oversupply of sponge and that several plants are not running at full capacity.

There is no market for titanium sponge in South Africa. South Africa does not yet produce the precursor ($TiCl_4$) or the successor (titanium melted products) for this stage of the titanium metal value chain. The local vision element for the South African titanium sponge production does not include a sponge plant within the next 10 years. The main reasons for excluding this plant is the high capital cost associated with building this type of a facility, the oversupply of sponge globally, the investment risks for industrial partners in South Africa and the local electricity supply crisis.

8. Chapter 8: Stage 5 (Melted Products)



8.1. Literature Review

The production of titanium metal is a complicated process. Titanium has a high inherent affinity for oxygen and oxidises readily (Fang *et al*., 2017). This results that titanium specialised processes and technologies to ensure that contamination is avoided or kept to a minimum. These specialised processes lead to high costs in fabrication as special conditions need to be maintained (e.g. an argon environment) during fabrication. Oxidised products have an inferior quality and depending on the metal application, these parts are mostly discarded as scrap. The literature review on melted products will focus on the technologies applied within this stage of the titanium metal value chain as well as the global outlook for this stage of the value chain. Melted products are not only produced from titanium sponge, but also from titanium scrap or a combination of the two.

8.1.1. Titanium Melted Products

The process steps to further beneficiate titanium sponge is by heat treatment to produce melted products (ingots, blooms, billets and slabs). The three main commercial methods used to produce melted products are vacuum arc re-melting (VAR), induction skull melting (ISM) and cold hearth melting (CHM). CHM includes electron beam melting (EBM) and plasma-arc cold hearth melting (Roskill, 2019). Out of these processes VAR is the most commonly used. Bomberger and Froes (1984) described the basic process steps for titanium melting as blending the raw materials for alloy production or only commercially pure (CP) titanium for unalloyed titanium production. Thereafter blocks are formed by pressing the materials together and finally welding the blocks into electrodes for melting.

The aim of forming an electrode ensures that the materials are homogeneously mixed. An electrode has poor machining and fabrication properties and requires additional processing to produce ingots, blooms, billets and slabs. Processing includes melting-electrode preparation, multiple melt sequences and intermediate/final conditioning. Ingots, blooms, billets and slabs are different sizes of the same thing and form the feedstock for titanium mill products (Roskill, 2019; Moyer *et a*l., 1994; Goso and Kale, 2011).

CP titanium is used for operations that require moderate strength, good formability and corrosion resistance. It has been available since 1950 as mill products with the leading industry being aerospace (Boyer, Welsch and Collings, 2007). Several grades of CP titanium are available each with its own properties related to impurities such as carbon, hydrogen, iron, nitrogen and oxygen. The four different American Society for Testing and Materials (ASTM) CP grades (a reporting standard for titanium alloys) are grade 1 to grade 4 of which grade 1 is the purest (Boyer, Welsch and Collings, 2007). The mechanical properties of pure titanium are greatly affected by its impurities.

8.1.2. Vacuum Arc Re-Melting (VAR)

VAR is the commercially dominant process to produce titanium melted products (Ji, 2013). During VAR a consumable titanium electrode is suspended in a vacuum furnace to be re-melted. Melting is initiated when the electrode (negative charge) comes in contact with a small bottom that is positively charged within the furnace creating a current (Bomberger and Froes, 1984). A liquid pool forms at the bottom as the liquid drops down (See Figure 32 A). After 90 % of the electrode has been consumed the power is reduced and the liquid titanium is left to solidify to produce an ingot with the required chemistry and structure (El Mir *et al.*, 2010; Ji, 2013). The VAR process ensures that a pure metal is produced through gradual melting and controlled solidification (Bomberger and Froes, 1984; El Mir *et al*., 2010).

8.1.3. Cold Hearth Melting (CHM)

Two types of CHM technologies exist namely Electron Beam Cold Hearth Melting (EBCHR) and Plasma-Arc Melting (PAM). Both these technologies are displayed in Figure 32. The two types are distinguished based on their heat sources, but other than that, they follow the same process flow namely melting, refining and casting. Melting and refining can both occur in the same hearth/vessel or each in their own. Once the heat source contacts the surface, the material melts. The molten titanium will then flow to the refining hearth where a second heat source applies more heat to ensure the metal remains molten. It is at this stage where impurities are removed by either evaporation, dissolution or density separation. In the last section, casting zone, the liquid metal will flow into a mould to form an ingot (Ji, 2013).

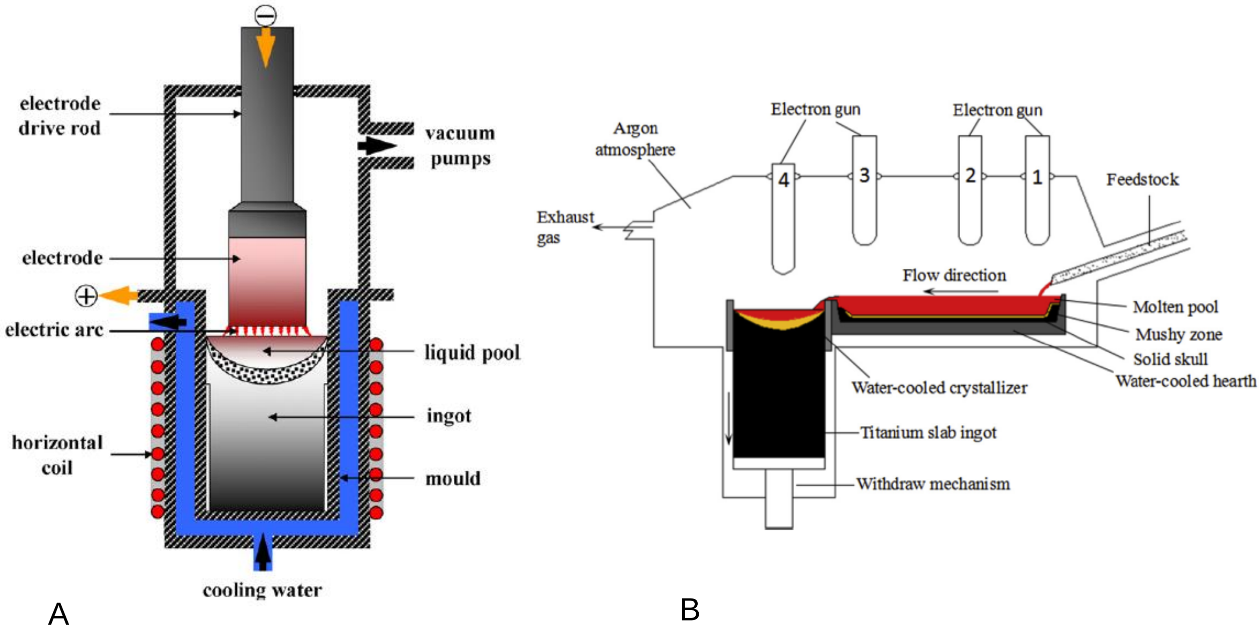


Figure 32. (A) Schematic diagram of a vacuum arc furnace and (B) Schematic diagram of a EBCHM (Source: El Mir *et al*., 2010; Liu, Li and Jiang, 2017).

EBCHR is the preferred and most common production method for titanium melted products (Ji, 2013). Compared to the traditional VAR melting, EBCHR produces a higher purity, more homogenous product (due to a longer residence time) and the technology has the potential to reduce the cost for ingot formation. This cost reduction is due to the elimination of the forging and stamping phase as the ingot can be directly rolled into strip coils (Liu, Li and Jiang, 2017). EBCHR is the preferred method for scrap melting. When a premium-quality titanium ingot is required from scrap, it is recommended to firstly subject the scrap material to hearth melting prior to VAR (Ji, 2013).

8.2. Global Outlook: Melted Product

Historically more melted products were being produced compared to mill products. Lately, thanks to improved processes and process efficiencies, this ratio has come down and as a result, less melted products discards are recycled as scrap. The losses that do occur are due to contamination that occurs during fabrication, especially during double and triple melting when the suppliers aim to reach aerospace grade titanium metal specifications (Roskill Information Services, 2017).

Globally the melted product capacity is around 543.3 ktpa but the output rate for 2019 was expected to be approximately half of that. The countries that produce the bulk of the melted products are USA, China, Russia and Japan.

Industry demand for melted products are driven by the need of aerospace grade mill products which require aerospace grade melted products. For 2019 the estimated requirement of aerospace grade melted products accounts to around 73 % of the capacity or 395 kt in 2019. This industry has more stringent requirements and fewer certified producers leading to a global demand for titanium melted products of aerospace grade. Aerospace grade melted products also require double or triple melting cycles preventing plants to reach full capacity.

China does not focus on this market as 80 % of their mill and melted products are of lower grade (for industrial markets such as desalination, nuclear and chemical processing). China is thus not focusing on producing for the aerospace market for melted or mill products (Roskill, 2019).

The melted product export market is small with the main exporters being the USA (more than half of the global exports), Russia and Kazakhstan. The main reason for the low export rates is that the producers of melted products tend to also produce the next stage of the value chain (stage 6, mill products) (Roskill, 2019). In 2018 the UK was the biggest importer of titanium melted products (7.2 kt) followed by Italy and France (3.7 kt each) (Roskill, 2019).

Melted product production generally exceeds sponge production due to the inclusion of scrap at this stage of the value chain. Countries where this have the biggest effect is the USA and Russia. China on the other hand uses relatively little scrap (Roskill, 2019).

The cost of melted products fluctuates over short periods of time. It should also be noted that there is not a huge market for melted product trade. The average cost (exports from US and Russia) for ingots by the second quarter of 2019 was US$ 15.50/kg and for slabs US$ 21.49/kg. Recent data is not available for melted products produced in China, but data from 2011 indicates that a lower price (compared to the other leading countries) was observed that could be related to the lower grade of titanium metal produced (Roskill, 2019). Global titanium melted product production is expected to follow the growth rate of mill products. Roskill (2019) expects that both these markets will grow at 2.3 %pa.

8.3. Where is South Africa now?

South Africa does not produce titanium melted products, but the country imports limited amounts of ingots for further fabrication into mill products.

8.3.1. Market (Where is South Africa now?)

Limited trade in melted products have been observed on a global scale. The main reason for this is because facilities that produce melted products also produce the mill products on the same site. The production of melted products is driven by the need for mill products and globally the biggest market is the aerospace market. According to the data obtained from the 2019 Roskill Report there is a demand on high-grade titanium melted products for the aerospace market.

No import or export data is reported specifically for melted products on Quantec EasyData (QuantecEasyData, 2019). This falls under a category called "*Unwrought titanium and powders*". Unwrought titanium includes titanium in its basic cast form made from primary metal or from scrap and is unworked in metallurgical terms. Based on the statement that minor trade occurs in melted products and the lack of processing facilities in South Africa it was determined that the bulk of the figures reported by QuantecEasyData (2019) represent the powder market and will be discussed under Chapter 10.

The import quantities of melted products are unknown, but according to interviewees this figure is very low and limited to research and large private companies producing parts for the military and defence industry. Limited to no information on these imports is available and local traders of titanium are hesitant to share market information.

8.3.2. Product (Where is South Africa now?)

South Africa does not produce titanium melted products (ingots, blooms and billets) as there are no melting facilities locally produced sponge as feedstock. All titanium ingots used in South Africa have been imported. Clients who require products manufactured from titanium ingots, billets or blooms would specify what product they require and therefore the quality of the metal. The product is therefore limited to the engineering capabilities in the local industry.

8.3.3. Technology (Where is South Africa now?)

South Africa does not have a titanium melting facility.

8.3.4. Research and Development (Where is South Africa now?)

Limited research has been conducted by local government organisations to produce titanium melted products. Historical research done in 1990s (confirmed by interviewees) contributed to the production of titanium alloys with superior corrosion resistance properties. Four ASTM titanium alloy grades were developed containing ruthenium. This research was driven by the abundance of platinum group metals

(PGMs) in South Africa and the aim to find alternative uses for the lower cost PGMs (Van der Lingen and Steyn, 1994; Van der Lingen and Sandenbergh, 2001; Potgieter and Van der Lingen, 2016; Sandenbergh and Van der Lingen, 2005). Interviewees also confirmed research on titanium alloying with other PGMs and combinations thereof, e.g. iridium, palladium and ruthenium, for improved corrosion resistance.

More recently researchers from the University of the Witwatersrand have studied the production of a new low-cost titanium alloy that could be used in non-aerospace sectors (Bodunrin, 2019). The proposed alloy would be an alteration of the commercial Ti-6Al-4V alloy by changing the element concentrations, especially replacing vanadium with more cost-effective iron. The preliminary studies were conducted using a vacuum arc melting furnace located at Mintek which can melt less than 100 g of titanium alloy. The need for a VAR facility to produce larger samples has been identified as a hurdle to advance the research.

8.3.5. Resources (Where is South Africa now?)

South Africa does not have the resources required to produce titanium melted products. A list of the absent resources is given below.

- Although South Africa has the fourth most abundant titanium mineral reserves, the country does not have the technology or capabilities to produce $TiCl_4$ or titanium sponge which are the precursors for titanium melted products.
- Although South Africa has relatively cheap electricity it currently has an unstable electricity grid. A melting facility is energy intensive and would require a constant and reliable energy supply.
- South Africa does not have the required skill set to operate a melting facility. Although these skills could be outsourced, they are not currently established locally.
- A melting facility would require a huge investment. According to the 2019 Roskill report globally such a facility is most accompanied by a mill product facility and the capital investment for both facilities will be huge.
- The feedstock for melted products is titanium sponge. This is not produced locally and according to the result of this research it should not be produced locally for the next 10 years.

It was indicated in the methodology section that raw materials (or feedstock) and human capital will be considered under resources. As indicated in the bullets above South Africa does not produce the feedstock for this stage of the titanium metal value chain (titanium sponge). PGMs, vanadium and aluminium (raw materials) are available in South Africa and used in titanium alloys. Although South Africa does not mine aluminium bearing minerals (bauxite) the country has an established aluminium processing industry indicating that South Africa also has a fragmented aluminium industry value chain. Although these alloying materials are available locally, interviewees noted that this is not an attraction to produce titanium alloys locally as the additives/alloying elements are available on the open market at fixed prices. Furthermore, a maximum 0.25 % PGMs are used in the alloys which is a very small quantity. As indicated in the bullet points above, South Africa does not have the required skills within its human capital pool to operate a local melting facility.

8.4. Vision Element: Where does South Africa want to go?

South Africa is not expected to have a titanium melting facility within the next 10 years, therefore no local activity (except for minimum R&D) in melted products is foreseen.

Although the vision states that no intervention is expected for the next 10 years, a longer-term readiness within stage 5 (melted products) is desirable. This readiness was highlighted by interviewees to ensure that a minimum knowledge base is built for the long run so the required skills are available if the opportunity presents itself. Knowledge on vacuum processes is important for the next stage (stage 6, mill products) as titanium casting and melting is generally done by VAR applications. This means that a common knowledge base will be beneficial for the country. This will mainly be addressed by recommending limited R&D for the next 10 years.

The majority of the survey opinions indicated that experts agree that South Africa should not have a titanium metal melting facility within the next decade. The key point raised on this was the lack of both $TiCl_4$ and sponge feedstock, the large take-off required for return on investment for such a facility and South Africa's current energy crisis. One disagreement argument stated that melting of recycled titanium to produce a lower grade titanium product (powder was recommended) should be considered to minimise value losses in titanium recycling. Titanium recycling will be discussed in more detail in Chapter 12, but the key point to note is that limited recycling capability in titanium has been established locally.

8.5. How will South Africa get there?

Based on the data collected from experts in the local titanium field, South Africa is not expected to have a titanium melting facility in the next decade. Results did however indicate that a melted product facility should be considered over the long run especially if a profitable scenario could be reached. Results from the interviewees are displayed in Table 21.

Table 21. Opinion analysis of interviewed experts on South Africa not having a titanium melting facility.

3 Years	10 years
71 % of the answers were negative regarding having a titanium melting facility in South Africa within the next three years	56 % of the answers were negative regarding having a melting facility in South Africa within the next 10 years.

Reasons for not having a titanium melting facility are listed below in decreasing order of importance. The reasons were ranked during the survey section of data collection.

- South Africa does not produce titanium sponge, the precursor for titanium melted products.
- South Africa is experiencing an electricity-supply crisis resulting in electricity restraints. This is placing pressure on large industrial companies that do not have a guaranteed access to electricity and ever-increasing electricity costs.
- This facility would be too capital intensive.
- When considering powder production from ingots, it would be cheaper to import ingots to produce a titanium metal powder (spheroidisation or atomisation) compared to producing the ingots locally.
- The bulk of the consumers of titanium melted products and titanium mill products are in the northern hemisphere. South Africa is located too far from the market and would not be able to compete on a global scale.
- South Africa does not have the required skills or experience with the technology.

Reasons for considering a titanium melting facility include:

- If South Africa wants a complete titanium metal value chain, a melting facility would be required to add value to the local titanium reserves (conventional sponge route).
- Some interviewees stated that South Africa could have both a $TiCl_4$ and sponge production facility up and running within the next 10 years. If this was to realise, then South Africa could also have a melting facility for additional value addition. Titanium scrap can also be reprocessed using this facility. This was the view of a limited number of interviewees and based on the bulk of the results, this view is seen as highly unlikely within the next decade.
- To systematically grow South Africa's fragmented titanium metal value chain (value addition). Even if South Africa does not have a complete titanium value chain the country should import titanium sponge and process it at a local titanium melting facility (estimated at US $ 50 million).
    - There is a demand for the aerospace grade Ti-6Al-4V alloy and South Africa could produce this alloy for the export market.

    - To supply local PM market at a cheaper cost compared to importing ingots for powder production.
- Socio-economic reasons: This facility employs skilled workers and will have multiple downstream employment benefits. This facility will therefore enhance HCD and employment opportunities.
- All the reasons mentioned for not having a melting facility could be addressed in 10 years with the appropriate support from government and investors.

8.5.1. Market (How will South Africa get there?)

The bulk of the interviewed experts indicated that South Africa should not consider having a titanium melting facility within the next decade. Although the number of interviewees convinced that this type of facility should not be considered for the long-term (7 year) period decreased, it was still concluded that the establishment of this stage of the value chain is highly unlikely within the next decade. Even though this means that the country should not be producing ingots, blooms, billets and slabs it does not mean that the local market does not exist. Interviewees predicted a small growth in the local melted product market driven by the maturation of the local mill product industry.

8.5.2. Product (How will South Africa get there?)

It is not foreseen for South Africa to produce melted products within the next decade. The import of melted products (ingots, blooms and billets) is expected to continue and grow together with the local processing capacity.

8.5.3. Technology (How will South Africa get there?)

South Africa does not have a large scale titanium melting facility. The complexity of this facility (vacuum chambers and re-melting facilities) has a direct relationship to the high cost and skills required to build and operate the facility. The value chain stage vision element for the next decade is for South Africa not to have a melting facility, but interviewees indicated that this should be revisited in the future. Globally the preferred technology is VAR as it is easy to operate and has a lower construction and operating cost compared to the other melting processes (Kosemura *et al*., 2002). If South Africa was to consider a melting facility the country would either need to import titanium sponge plus set up a VAR melting facility, or setup both a $TiCl_4$ and sponge plant together with a melting facility. Both options are highly unlikely within the next decade.

8.5.4. Research and Development (How will South Africa get there?)

The conclusion for this stage of the titanium metal value chain (melted products) is that South Africa should not have a titanium melting facility within the next decade. A need for a minimum knowledge base was however identified. This minimum knowledge base could consist of the country investing in developing local skills in alloying and melted product production. This should first be done on lab scale using locally recycled titanium scrap as well as imported titanium sponge. Alternatively, South Africa should find an industrial partner who already has access to the required skills and technologies and through the partnership establish a melting facility locally. Training should then be provided to local employees to develop skills. Research should be conducted on how to incorporate renewable energies into the proposed VAR plant design. This is not expected to occur within the next decade.

The research discussed in the "Where is South Africa now?" section on the laboratory scale VAR furnace to produce a new cheaper titanium alloy is a positive step for South Africa. This research needs to be scaled up and the appropriate VAR technology needs to be obtained. In order to build the skills and understanding of the process this experimental research should follow the technology readiness levels of laboratory scale, pilot plant scale, followed by commercial scale. The construction of a commercial scale plant should only be considered after a techno-economic analysis that should look at the feasibility of establishing this stage of the value chain locally. This analysis would be able to indicate whether South Africa will be able to produce a product (from imported sponge and scrap) that can compete in the export market. Therefore, there is a need to do a market study on the feasibility of producing melted products from local scrap as well as from imported titanium sponge. All CHM technologies should be revisited in the future to ensure that VAR technology remains the most suitable.

8.5.5. Resources (How will South Africa get there?)

The feedstock for melted product production is titanium sponge. This is not produced locally and according to the outcome of this research, it should not be produced for the next 10 years. One alternative, presented by interviewees, was the establishment on a trade agreement between South Africa (that produces the raw titanium minerals) and a sponge producing country (that processes the South African mined minerals). Titanium sponge could then be imported through this trade agreement or from the free market if that was the cheaper option. Alternatively, titanium scrap could be used as feedstock. South Africa does however have access to elements such as PGMs, vanadium, aluminium and iron needed to create popular alloys. The availability of these elements was already discussed in the "Where is South Africa now" section, where it was stated that this is not a strong driver and will therefore not be included on the roadmap.

South Africa should build on its human capital. The main industries producing melted products are the steel and aluminium industries. Steel and aluminium have simpler processes to produce melted products as they do not require inert atmospheres or secondary melting. These conditions are important for titanium melts as liquid titanium reacts rapidly with all gasses, except inert gases such as argon and helium. This requires technologies that can prevent contamination. An example of such a technology is working in a vacuum or VAR. Building a minimum knowledge pool within the complex titanium melting industry will mean that local skills will be available when a related opportunity arises and in addition the human capital that is developed would be able to be applied in the simpler industries.

8.6. Discussion: Roadmap for Titanium Melted Product Production

South Africa is not foreseen to have a titanium melting facility within the next decade. Chapter 8 elaborates on the results obtained from literature as well as experts in regard to the local production of titanium melted products. Except for minor imports of melted products South Africa is not involved in this stage of the titanium metal value chain and no local activity in melted products are foreseen for the next decade. Table 22 is a summary of the results obtained for Chapter 8.

Table 22. A summary of titanium melted product production (stage 5).

Where is SA now?	Market	• Import limited amounts according to real need
	Product	• None
	Technology	• None
	R&D	• Limited historical R&D on alloy production • Ongoing research on low-cost titanium alloy for non-aerospace sectors
	Resources	• Relatively cheap electricity compared to first world countries
Where does SA want to go?	Vision element	*South Africa is not expected to have a titanium melting facility within the next 10 years, therefore no local activity (except for minimum R&D) in melted products is foreseen.*
How will SA get there?	Market	• Small growth in the local melted product market driven by the maturation of the local mill product industry
	Product	• None
	Technology	• None
	R&D	• R&D in alloying and melted product production should continue (VAR technology) • VAR technology (currently lab scale) should be expanded, and a bigger pilot scale plant should be built • A techno-economic study on the feasibility of implementing commercial scale VAR technology in South Africa before building an even bigger plant. This should be done on lab scale and grow from there as competency grows • The R&D research should focus on locally recycled titanium scrap but also include imported titanium sponge • Market research should be started on the need for producing melted products from imported sponge • R&D on incorporating renewable energies into proposed VAR plant design
	Resources	• Skills to be established through VAR research • Relatively cheap electricity & an increase in renewable energy

Table 22 clearly indicates that this stage of the titanium metal value chain is not yet established in South Africa and that its possible implementation is not likely within the next decade. The results displayed in Table 22 followed the generic technology roadmapping layout presented in the methodology section. This layout was used to create a roadmap for titanium melted product production displayed in Figure 33.

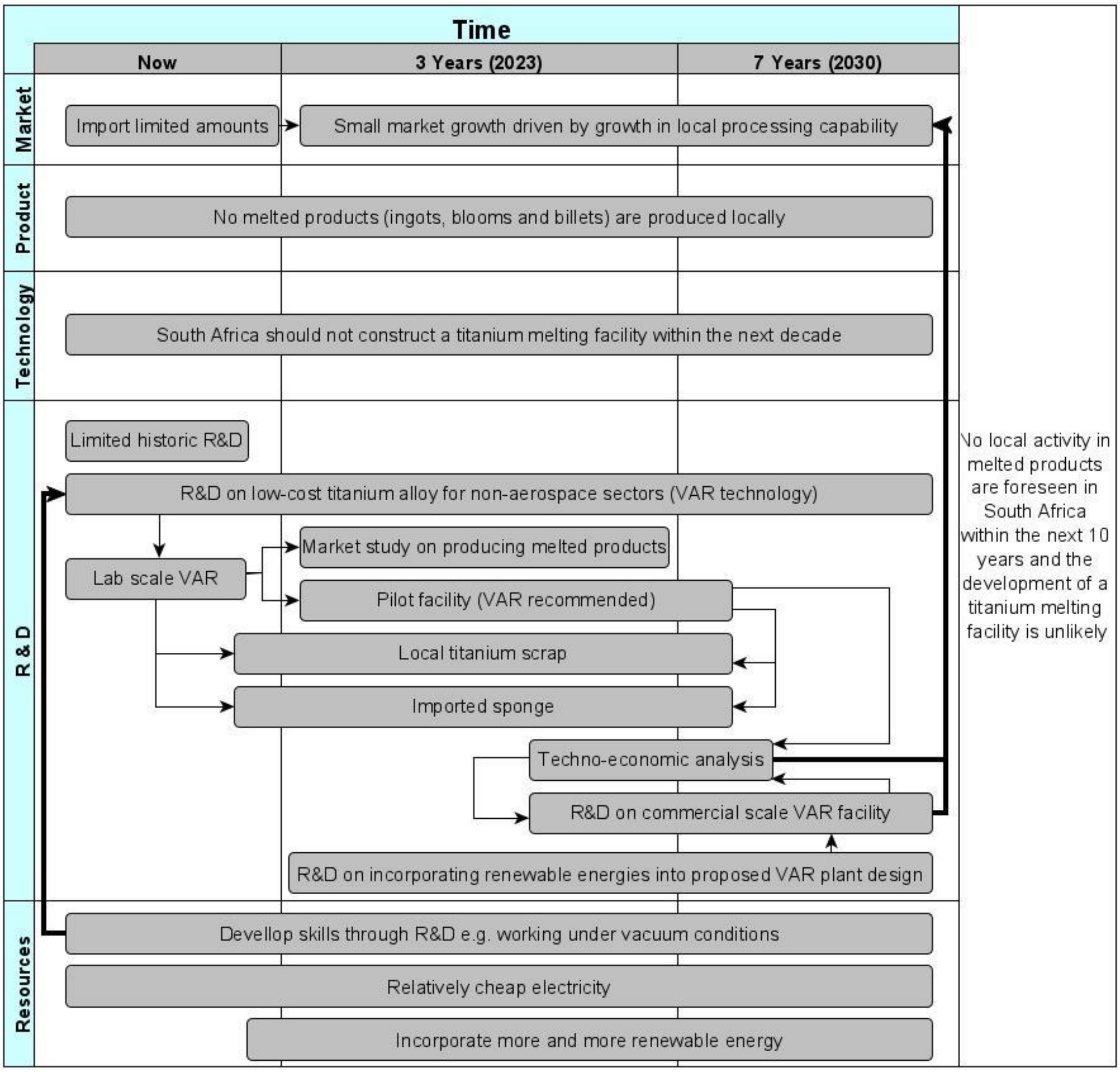


Figure 33. The local 10 year roadmap for titanium melted product production (stage 5).

Figure 33 indicates that no melted products are produced locally but limited amounts are imported for further processing. It is expected that the local market for titanium melted products will grow slowly during the next decade as the local awareness of titanium metal is increased and thereby a growth in local processing capability. The growth within the local market would be sustained by imported melted products.

Although the establishment of a local titanium melted product stage of the value chain is not foreseen for the next 10 years, local research on this stage is being conducted. Historically limited R&D was conducted on titanium melted product production. This was due to the unavailability of suitable VAR facilities resulting in the research being pursued by involving international collaboration.

Current research on the production of titanium melted products aims to produce a low-cost titanium alloy for non-aerospace sectors. This R&D has been conducted using lab scale VAR technology. Experts indicate that although this stage of the local value chain is nonexciting locally, this type of R&D should continue, to create a state of future readiness should a new market opportunity arise beyond the scope of the 10 year vision of this roadmap. A need has been identified for a market study on melted product production to obtain a better understanding on the feasibility of continuing this research locally (to be conducted within the next three years). At the same time a larger pilot facility (recommended to be VAR) should be constructed, pending the outcome of this feasibility study, to allow for improved R&D. VAR is the most commonly used melting technology and there is already a R&D bases built in South Africa. The research conducted on both the laboratory scale and pilot scale should use local titanium scrap as well as imported sponge as feedstock as no sponge is foreseen to be produced in South Africa within the next decade.

Based on the results obtained from the proposed market study a techno-economic assessment on the construction of a commercial scale VAR facility should be conducted. If this assessment indicates that South Africa should consider building a VAR facility R&D on such a facility should be started. It is not foreseen that a commercial titanium melting facility would be feasible within the next decade. In conjunction with the R&D on VAR technology, South Africa should also investigate the incorporation of renewable energies into the proposed VAR plant design. This would ensure a reduced carbon footprint as well as ensuring a more stable energy supply to the facility.

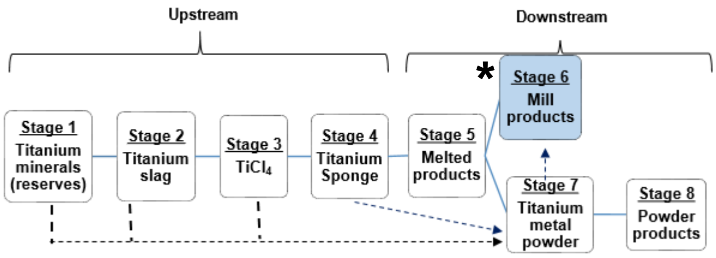
8.7. Chapter Summary

Chapter 8 focused on melted product production. Melted products are produced though the melting of sponge. It is at this stage of the value chain where the decision is made to produce a CP titanium or a titanium alloy. The different processes for melted product production as well as the further processing of the electrodes were described in the literature review section of Chapter 8. For CP grades only pure sponge is used for further processing, but for alloy production raw material blending is done and the blend melted together with the sponge. Once melted, blocks are formed by pressing the material together. The blocks are then welded together to form an electrode that would be exposed to additional melting to ensure homogenisation of the blended material in the ingot. Ingots are further processed to form blooms, billets or slabs.

It is not foreseen that South Africa will have a titanium melting facility within the next 10 years. The main reasons associated with the absence of this stage of the titanium metal value chain are: the absence of locally manufactured sponge as feedstock, unreliability in South African' electricity supply, and the capital required to build such a facility being too high. It would be cheaper to import ingots instead of producing them locally. South Africa is also too far from the market to compete internationally. All the countries that have complete titanium metal value chains are in the northern hemisphere making trade distances shorter and thereby the product distribution cost cheaper.

The production of titanium metal through the conventional sponge process includes the melting of titanium sponge (and/or scrap) to form titanium melted products. Globally several technologies have been perfected to ensure this process produces clean and un-contaminated melted products. The preferred process to use is VAR and this trend is also dominating the local R&D. Although South Africa is not expected to have a commercial titanium melting facility within the next 10 years, R&D is actively being conducted on the production of titanium alloys. This is related to the country building a minimal knowledge base that could be applied when the opportunity presents itself as well as the benefit such skills and knowledge will have on the downstream titanium metal value chain (especially mill products, stage 6). The main drawback for R&D is the absence of a sufficient size VAR facility. The roadmap generated for this stage of the value chain therefore indicates that a pilot scale melting facility should be constructed within the next three years. This pilot scale melting facility should then be followed by the conduction of a feasibility study towards the construction of a commercial facility. This study should be conducted towards the end of the decade.

9. Chapter 9: Stage 6 (Mill Products)



**It is important to note that when referring to mill products in this thesis it will not only include intermediate mill products produced from melted products, but also products fabricated from intermediate mill products referred to as final mill products. Mill products therefore includes fabricated products.*

9.1. Literature Review

Titanium mill products make out the largest portion of titanium products. This section of the value chain is dominated by the aerospace industry and followed closely by the chemical industry. The literature discussed in this section will look at the different mill products being produced globally and why these products are made from titanium instead of other metals. Several technologies used to produce mill products will also be discussed.

9.1.1. Titanium Mill Products

Titanium mill products are any product produced by processing melted products. These processes could include wroughting (e.g. forging and rolling) and casting (Donachie, 2000). Mill products are produced in various sizes and shapes which are either the final product or an intermediate product that will later be fabricated into final components. The most general forms of mill products are billet, bars, rods, wire, plate, sheets, forgings and castings (Roskill, 2019).

Wrought products have a slight advantage on tensile strength when compared to cast-plus hot isostatic pressed (HIP) products. Although wrought products are more common, titanium products produced by casting and especially investment casting are cheaper. This is due to a weight saving and less titanium metal is wasted during the production process of near-net-shaped (NNS) parts (Donachie, 2000). NNS processes have been researched for over 50 years (Chen, 1982), and have several advantages over conventional forging methods with the main advantage being a reduction in cost. When applying NNS processes the amount of material used is significantly reduced as the desired shape is created from only one step. This also results in less material being used and therefore less waste being generated. The products created by the NNS process do not need further machining and therefore results in a further cost reduction. By applying NNS processes the microstructure and properties of the product are precisely controlled and therefore the quality of the product is controlled (Chen, 1982; Froes, Gungor and Imam, 2007).

9.1.1.1. Wroughting

Wroughting can be defined as any hot or cold working of metal. The top two subsets of wroughting are forging and rolling. During forging a piece of metal (cold, warm or hot) is formed into the desired shape by localised compressive forces (blows). The "blows" are delivered by hammering, pressing, rolling, squeezing, and other such operations in one or more forging equipment (BusinessDictionary, 2019). During the forging process the force is applied through gravity or a supplementary force such as steam or air pressure acting on a hammer. The two basic methods for forging titanium are the open-die and closed-die methods (Total-Materia, 2007a).

Titanium forging usually occurs at a lower temperature than for forging conducted on steel to restrict surface contamination and prevent excessive grain flow. As a result of the lower temperature a higher pressure is needed for the forging of titanium metal (Total-Materia, 2007a). Forging can be viewed as the primary approach to derive shape and structure control in titanium alloy components. This is also very important process to ensure that the mechanical properties are achieved which do not exist in its melted product precursor (Donachie, 2000).

Titanium rolling is the main method used for the commercial production of titanium plate, sheet, strips and bars. Rolling can be loosely defined as the reduction of cross-sectional area of a piece of metal by compressive forces applied through rolls (Total-Materia, 2007b). The main types of rolling used to produce titanium rolled products are hot and cold rolling (Donachie, 2000). Before titanium rolling can occur, the surface of forged billets needs to be scaled to remove any contamination.

9.1.1.2. Casting

Casting is a manufacturing method where titanium metal is melted, and the liquid is injected or poured into a mould that already has the desired shape. Once solidified the cast is broken out of the mould (BusinessDictionary, 2019). When casting titanium, melting is generally done by vacuum arc heating which is basically the same method that is used during the production of titanium melted products. This means that ingots produced from alloys can easily be casted to form net-shape products (Froes, 2015a).

The casting process is the most wide-spread and cost-effective titanium net-shape technology, but the process also comes with its own set of challenges. Molten titanium has a high reactivity resulting in most of the melting being done under vacuum in vacuum arc furnaces. Another aspect to consider is that the microstructures and inherent porosity of the part obtained during casting displays reduced mechanical properties compared to parts produced through ingot metallurgy. The result is a product that is unsuitable for demanding applications unless it is treated further. One such treatment technique is HIP which improves the mechanical properties by completely healing or partly closing pores (Froes, 2015a).

The most common titanium casting technology is consumable electrode arc melting, the second most common is the rammed graphite mould method and the third most common is the investment casting method. (Froes, 2015a). Post-casting treatments include HIP and further heat treatment. During the HIP process a heated, argon filled pressure vessel is used to densify titanium castings. As mentioned, the aim is to eliminate the voids and to decrease the porosity of the parts (Froes, 2015a). There are two types of heat treatment used on titanium castings. The first is a stress-relief treatment that aims to relieve the residual stresses captured in the part during casting and HIP. The second heat treatment is applied to change the microstructure of the cast product and thereby improving the mechanical properties (Froes, 2015a).

9.2. Global Outlook: Mill Products:

The global production of mill products is highly dependent on the three precursor stages of the titanium metal value chain, namely $TiCl_4$ production (stage 3), titanium sponge production (stage 4) and titanium melted product production (stage 5). This is due to the ownership and location of production for these three stages. The monopoly of the three core stages of the titanium value chain allows the major producers to capitalise on downstream value addition and to use the knowledge of titanium processing and titanium scrap handling to their advantage (Roskill, 2019). The result of this is a cheaper mill product cost as the process streams from $TiCl_4$ production, to sponge production, to melted product production and finally mill product production complement each other. This is especially true for the mass production of intermediate mill products such as sheets, bars and pipes.

The global capacity of mill product production for 2019 was estimated to be over 200 ktpa. In 2018, 184 kt of mill products were produced across the globe. Countries where the bulk of mill products were produced in 2018 were China (34 %), the USA (28 %), Russia (18 %) and Japan (10 %). These four countries also have matching sponge and melt capacities for titanium, reinforcing the statement that having these three core production stages are beneficial for promoting a country’s titanium metal value chain (Roskill, 2019).

Comparing the annual production of mill products against sponge and melted production this figure is lower owing to losses that occur during fabrication. Over the last five years this gap has been challenged through efficiency improvements along the titanium value chain allowing for less titanium waste generation. Improvements include hearth melting, water jet and wire electrical discharge machining as well as NNS production techniques (Roskill, 2019).

The trade of mill products is geographically diverse. This is in contrast with trade of sponge and melt products where the bulk of the products was upgraded within the same country (vertical integration) and mostly same company. The trade of mill products is twice as large as for titanium sponge (rather processed into mill products than traded as sponge) and four times as large as for melted products. The export matrix of titanium mill products traded in 2018 is displayed in Figure 34.

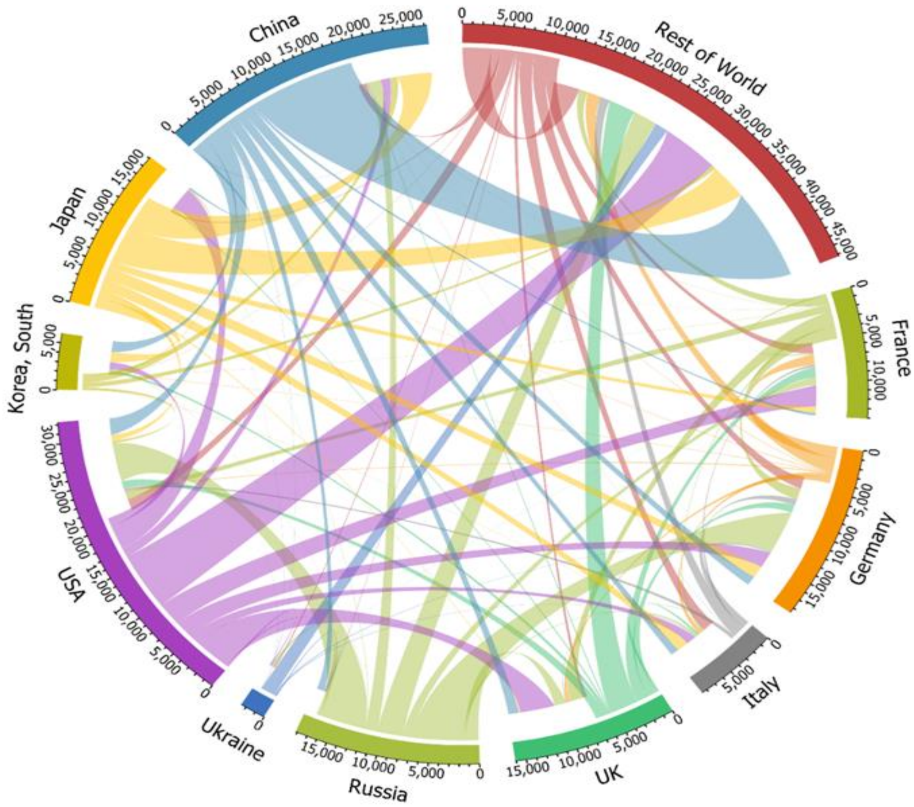


Figure 34. Export matrix of trade in titanium mill products, 2018 in tonnes (Source: Roskill, 2019).

Based on the trade data it is observed that the bulk of the titanium mill product trade remains in the northern hemisphere. The biggest exporter of titanium mill products shifts between the USA and China. In 2018 the biggest exporter was China with 19 kt and the USA were second with 18 kt. For the same year the biggest importer of titanium mill products was the UK with 17 kt followed by France and Germany at 12 kt and 11 kt, respectively. The products that were mostly imported were (based on weight):

- forged rectangular or flat products such as sheet and plate (34 %),
- extruded cylindrical products such as bars and rods (32 %),
- tubular products such as tubes and pipes (7 %), and
- other forms (27 %).

The price of titanium mill products varies depending on the degree of value addition during the manufacturing process. The average 2018 international trade prices for mill products are displayed in Figure 35.

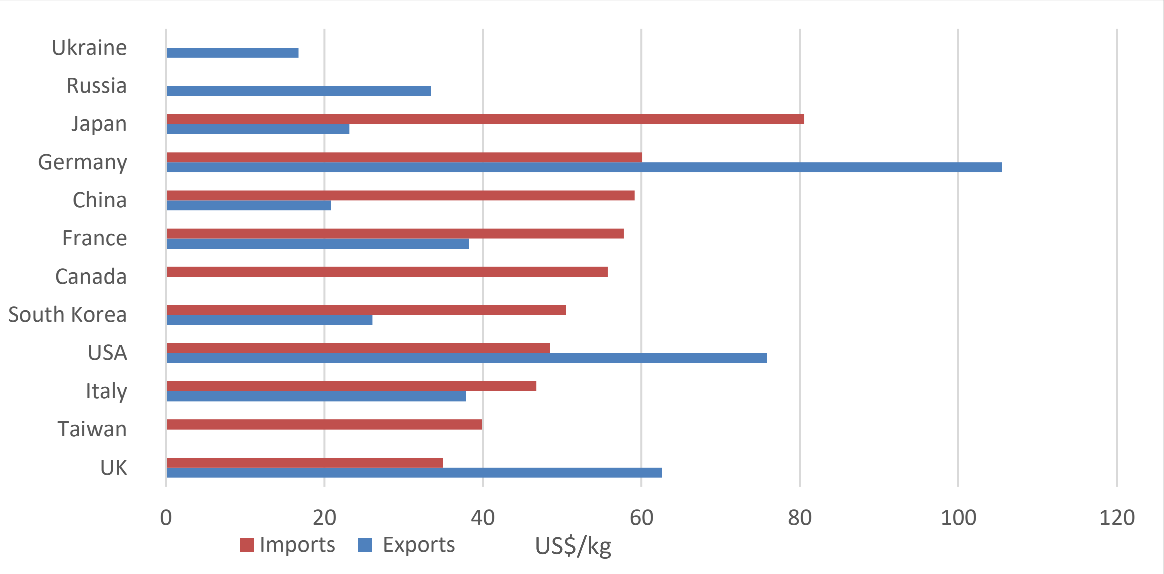


Figure 35. Average international trade values for titanium mill products, 2018 (Source: Roskill, 2019).

In 2018 the highest average export price (blue in Figure 35) for mill products were achieved by Germany (US$ 105.54/kg). On the other side of the scale Ukraine's exported mill products reached the lowest price (US$ 16.74/kg). Both countries exported small quantities of titanium mill products. China and the USA on the other hand are larger contributors to the global titanium mill product trade. From Figure 35 exports from the USA (US$ 75.83/kg) have a higher price per kilogram compared to China (US$ 20.79/kg). This is related to the higher-grade products (especially for the aerospace industry) that is produced in the USA compared to the lower grade (industrial titanium products) produced by China. The import price (red in Figure 35) for titanium mill products are slightly more concentrated with Japan paying the most for imports at US$ 80.55/kg and the UK paying the least at US$ 34.93/kg (Roskill, 2019).

South Africa's mill product market is dominated by the aerospace, medical and chemical industries. Locally these markets are expected to grow within the next decade and products are expected to follow global trends. Potential products for these three industries, observed from a global market perspective, are subsequently discussed in more detail.

9.2.1.1. Mill Products for the Medical Industry

The use of titanium within the medical industry started as early as the 1950s. Titanium has a number of properties that make it the material of choice for many medical procedures requiring mechanical implants. Titanium is mainly used in orthopaedics, as dental implants, as medical tools and as medical equipment (Roskill, 2019). The most common use within this industry is in the stems of hip replacement prosthetics. Table 23 is a summary of where titanium is used within the medical industry.

Table 23. Medical applications of titanium metal (Source: Roskill, 2019).

Application	Comment
Hip replacement	Most common biomedical use of titanium.
Knee replacement	Titanium used in around half of cases.
Other joints	Shoulder and elbow joint implants commonly made from titanium.
Fixation devices	Reconstructive bone plates, mesh, screws, rods, hooks, nails, cable and staples can all be made from titanium. Titanium pegs can be used to attach false eyes and ears.
Spinal fusion	Titanium cages are commonly used in spinal fusion procedures.
Cranioplasty/neurosurgery	Titanium plates and mesh are used to speed up operations and recovery and reduce chances of infection.
Maxillofacial prosthetics	Titanium implants used.
Rib cages	Expandable titanium rib cages allow for growth of child patients.
Treatments related to heart conditions	Titanium heart valves may be used, and titanium finds use in pacemaker cases, vascular access ports and coronary angioplasty catheters.
Hearing aids	Bone conduction hearing aids are anchored with a titanium device that connects to the middle ear.
Urethral stints	Titanium used in the treatment of urethral strictures.
Medication pumps	Ti-Ni shape memory alloys used in medication mini-pumps.
Dentistry	Dental implants are commonly made from titanium. Other applications include bridges, crowns and orthodontic braces.
Extremities	Titanium is used in finger and toe implants.
Medical instruments	Including forceps, retractors, tweezers, suture instruments, scissors, needles and micro-needle holders, dental scalers, dental elevators, dental drills, laser eye surgery equipment, laser electrodes, stents, staples, blades, marker bands and surgical clips.

Both CP grade and titanium alloys are used within the medical industry. As the biggest titanium market is within orthopaedic implants it is safe to assume that the biggest component of this industry is mill products, specifically forgings from bars. Table 24 indicates the a few selected often used parts and their processes for the medical industry.

Table 24. Processes used to produce titanium mill products for the medical industry (Source: Roskill, 2019).

Part	Process
Hip stems, knee tibial components, hip cups and knee femoral components	Forged
Trauma screws and hooks, spine components	Machined
Trauma internal components	From plate

Titanium usage in the cost-conscious medical industry encounters more competition than the aerospace industry. The biggest metal competitors within the orthopaedic industry comes from readily available and cheaper stainless steel and cobalt-chrome. Except for other metals, another big competitor for titanium mill product parts for the medical industry is titanium parts produced through AM (Roskill, 2019). This will be discussed in more detail later, but the competition is caused by highly patient-specific parts and a lower cost part that is available to the market.

9.2.1.2. Mill Products for the Chemical Industry

The chemical/petrochemical industry for titanium metal is a sub-category for the industrial application of titanium. The other sub-categories are the power, oil and gas, water supply, automotive, marine and construction industries. These industries follow a more generic trade trend as there are more competition from other high-performance alloys combined with the lower specifications compared to the aerospace industry. Figure 36 indicates the uses of titanium within the industrial application sub-categories.

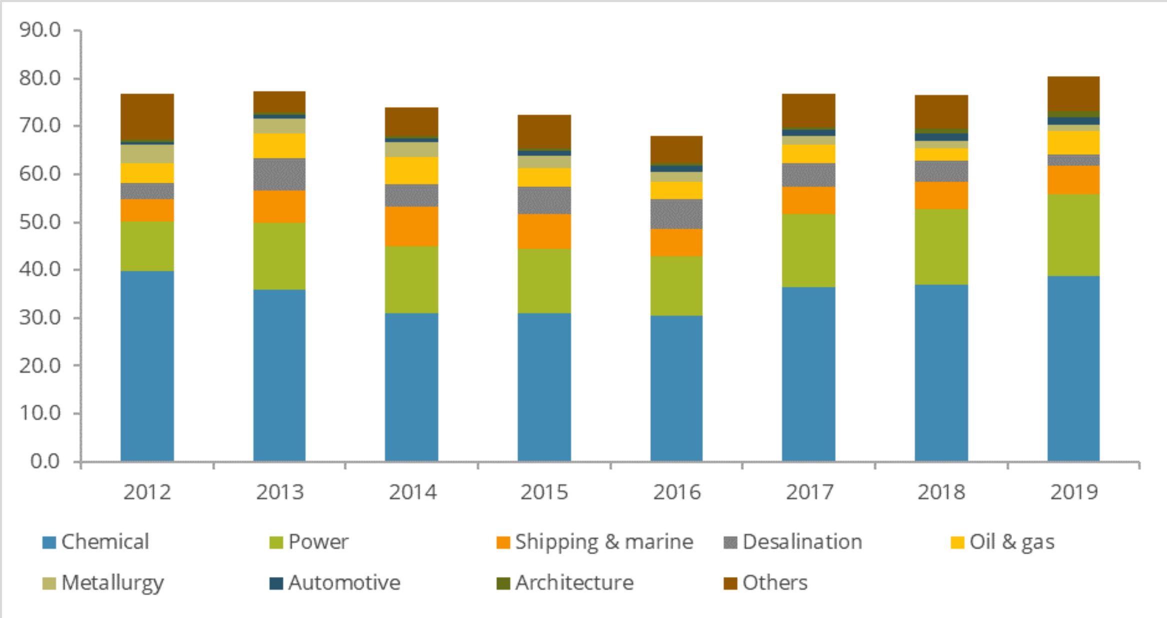


Figure 36. Industrial uses of titanium, 2012-2019 in kt (Source: Roskill, 2019).

Figure 36 indicates that globally the chemical industry is the biggest sub-category within the industrial use of titanium. The estimated market for mill products within the chemical industry for 2018 was 37 kt, with China utilising approximately 67 % of the parts (Roskill, 2019). According to Roskill (2019) the large uptake by China is not only attributed to its fast growing economy, but it may also be due to the Chinese doing the mathematics behind the return on capital cost over a longer time period combined with the overall abundance of CP grade titanium in China.

Within this industry CP titanium is the most popular and this is due to its corrosion resistance. Other tailor-made alloys are also maturing in this industry and development is taking place as required. The main applications for titanium within all the industrial sub-categories are in heat transfer equipment and then as tubes, pipes, tanks, vessels, fittings and fasteners. For these applications products are supplied as flat products, seamless tubing and bars. The most popular flat products include plates and sheets. Welded tubes are produced from strips which are cut from sheets (Roskill, 2019).

Within the chemical industry the chlor-alkali market is the largest with growth driven by the expanding Chinese market to produce chlorine. Titanium electrodes are the preferred electrodes during the production of chlorine and caustic soda. Other chemical production lines that utilise significant amounts of titanium metal is the production of purified terephthalic acid (PTA) (feedstock to produce polyethylene terephthalate for use in fabrics and plastic packaging), food processing equipment, cathodic protection and electrochemical applications.

The outlook for titanium within chemical applications is expected to grow from 37 kt in 2018 to 46 kt by 2029. This is mainly based on mill products as the parts are simple to fabricate and large quantities of the same sheet or pipe would be produced (mass production). AM could have a limited impact on the growth of mill products for this industry, but this would be restricted to complex shapes. The largest threat for this industry is a decrease in global economic growth that would have an effect on growth in the chemical sector (Roskill, 2019).

9.2.1.3. Mill Products for the Aerospace Industry

Titanium has a long and established relationship with the aerospace industry as the first commercial use of titanium was for jet engine parts as the metal systematically replaced heavy steel parts. The titanium replacements allowed the engines to achieve design potential as titanium weighed much less, but still provided the strength required (Roskill, 2019). The overall use of titanium in aerospace can be divided into two main uses which are for the engine and for the framework. Historically Ti-6Al-4V was used for jet engine blades and both Ti-6Al-4V and CP grade 4 titanium was used for airframe applications (Froes, 2015b).

The bulk of the current consumption of titanium in aerospace is used in jet engines (more than 35 % of all titanium shipments) (Froes, 2015b). A gas turbine engine (a type of jet engine) is composed of a variety of alloys. In the engine titanium metal is incorporated in the inlet case, the fan blades, the fan disks, the fan exit struts, the fan duct, the fan duet fairings and the rear compressor blades. The main reasons for using titanium on these parts are the metal's buy-to-fly ratio, the metal's ability to have a high fatigue strength at high-temperature, it has a low modulus with a high strength-to-weight ratio and titanium exhibits an exceptional resistance to corrosion (Froes, 2015b). When comparing the titanium metal used to the titanium metal discarded the ratio is referred to as the buy-to-fly ratio or the yield ratio (Fang *et al*., 2017). For the aerospace industry the required properties are mainly obtained through forged titanium alloys. Table 25 is a summary of the mill product production routes used to produce aerospace parts.

Table 25. Manufacturing of parts (Source: Froes, 2015b).

Part	Process 1	Process 2
Blades and disks	Close die forged or precision forged (NNS)	Machined to final product
Seals, spools (multistage disks) and engine cases	Ring rolling	
Compressor cases and structural housing members	Casting	Hot isostatic pressing
Ducts, fan cases and engine cases	Fabricated plate and sheet metal structures	
Melted titanium product for engines	Cold-hearth melting (lower O and N contamination)	
Hollow blades for high temperature applications	Superplastic forming coupled with diffusion bonding	

Aircraft design trends lead to bigger and faster products, therefore the use of light weight titanium alloys is increasingly observed. One area where an aircraft can save a significant amount of weight is on its airframe. An aircraft's airframe is composed of its fuselage, wings and its undercarriage. Some application examples for where titanium alloys are used, are as fasteners, springs, hydraulic tubing, in fracture critical applications and as landing gear and flap tracks (Froes, 2015b)..

The buy-to-fly ratio within the aerospace industry is extremely high and approximately 82 % of the titanium become scrap metal (Fang *et al.*, 2017). The average buy-to-fly ratio for the industry is 5:1 and 6:1, but a ratio as high as 20:1 exists for particular applications. Engine production has a higher ratio compared to airframes. Casting and AM processes are challenging the high buy-to-fly ratios, but both processes are limited to smaller components (Roskill, 2019). AM will be discussed in Chapter 11.

Globally the titanium casting abilities are capped at casts weighing 500 kg. The titanium casting industry holds great potential as it has brought the buy-to-fly ratio of titanium parts for newer aircraft models to 3:1 and 4:1. A UK university is also claiming that they will be able to produce casts with a ratio of 1.5:1 which would be a tremendous saving within the titanium industry (Roskill, 2019). Based on the size limitations involved in PM applications the traditional market for titanium mill products is not in immediate danger. An alternative option to produce cheaper titanium mill products for the aerospace industry is by casting of titanium and its alloys.

9.3. Where is South Africa now?

After not being involved in three consecutive stages of the titanium metal value chain (stages 3 to 5), South Africa is again involved in the mill product stage (stage 6). The extent of this involvement is not well documented as there is a shortage in the availability of accurate data.

9.3.1. Market (Where is South Africa now?)

Mill products can be classified into final products or intermediate products. The bulk of the local machining capabilities is to process intermediate products into final products. South Africa has an established, but small market for titanium mill products with a handful of local companies producing these products and the larger portion being imported. Information from these companies are limited and the quantities of melted and intermediate mill products being imported on a yearly basis are unknown. Engineering companies have reported that they have milling, turning and machining capabilities and these companies do undertake ad hoc titanium mill product jobs. Industries that have reported the production of titanium mill products in South Africa are aerospace, medical, marine and chemical.

The QuantecEasyData (2019) database does not report on mill product imports or exports directly, but the only category where these products fit is under “other”. According to Quantec staff, the SARS documentation does not specify what is included in the “other” category but stated that information from alternative trading partners’ websites indicates that the code includes titanium sheeting, rods, nuts, bolts and mounting brackets. According to a local distributor of titanium mill products the bulk of the imported titanium consist of bars (Extra Low Interstitials (ELI) grade, mainly for medical application), sheets (unknown application) as well as bolts, nuts and washers (mainly for marine application). Local imports and exports for the category “other” over the last five years are displayed in Figure 37.

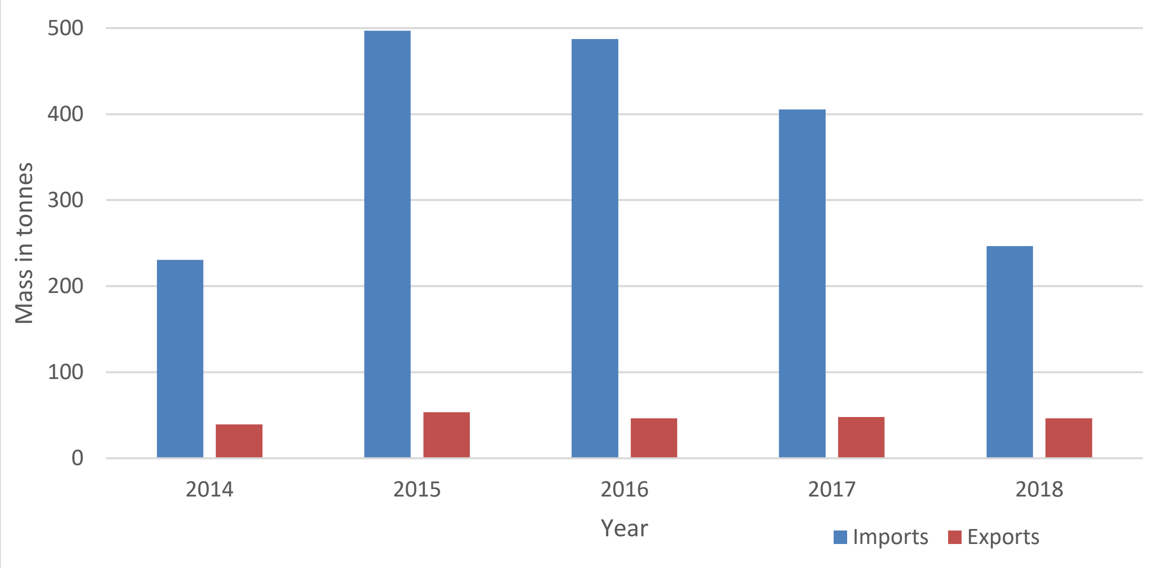


Figure 37. Annual South African import and export data for "other*" titanium parts (*other includes titanium sheeting, rods, nuts and bolts and mounting brackets) (Source: QuantecEasyData, 2019).

From Figure 37 the import market is much bigger than the export market. This could be attributed to South Africa mainly importing finished parts for end use applications and the fact that the local machining capabilities of intermediate parts are limited. Finished parts obtained from the machining of rods (especially in the medical industry) are already competing in the export market as interviewees stated that up to 65 % of the locally produced parts (mostly dental) are exported. Figure 37 also indicates that imports of mill products peaked in 2015 and decreased with nearly 50 % in 2018. The reason for this drop is unknown. The imports for 2018 was 246 t and the exports 47 t (QuantecEasyData, 2019).

According to interviewees there are two main factors preventing growth of the titanium mill product use in a South African context. The first is that titanium metal is an unknown metal locally and only a handful of industries are applying this metal in their sector. Interviewees also indicated that in order to shift/replace the conventional use of other metals with the use of titanium, a cultural shift and awareness campaign on the properties and capabilities of titanium metal as well as pricing barriers are needed. This relates to the second factor which is the high cost of titanium metal and therefore mill products. The machining of titanium alloys adds approximately 30-40 % to the total cost of the final mill product (Bodunrin, 2019).

9.3.2. Product (Where is South Africa now?)

South Africa does not produce intermediate mill products such as sheets, plates, bars, rods and pipes, therefore these parts are all imported. Most of the finished titanium products/parts are also imported and sold to the client mainly through a middleman (an agent). The import requirements for intermediate titanium products (bars, sheets and pipes) are dependent on the capabilities of local engineering companies (if additional processing is required) and the product requirements of the client. Although limited amounts of companies are fully dedicated to titanium mill product fabrication, the bulk of the engineering companies apply milling and processing techniques suitable for other metals (especially stainless steel and copper) to produce titanium mill products. Roskill (2019) reported on the potential of applying milling and processing techniques used in the stainless steel and copper industries for titanium processing, and this relates to South Africa as well.

South Africa hosts one of the leading global medical companies for dental implants. This company machines titanium implants from titanium rods. This industry is seen as an international player as only 35 % of the products produced are utilised locally and 65 % of the implants are exported to the global market. Products that are being produced for the medical industry are orthopaedic implants, dental implants, medical tools and medical equipment.

A leading South African aerospace company reported on machining titanium in their workshop using general milling equipment. It should be noted that the titanium parts that required cutting were non-critical parts of the aircraft. The company also specified that titanium machining applications are limited as the major concern is contamination of the aluminium scrap that requires a high purity for recycling, and bigger titanium machining jobs are therefore outsourced. Critical parts have been identified as critical by the design approval holder during the product type validation process. Failure of critical parts could have a catastrophic effect (European Union Aviation Safety Agency, 2020). Non-critical parts are the opposite of this and are not as strictly manufactured. Upon failure non-critical parts can be replaced without major damage or consequences (such as safety buckles).

The extent of using titanium mill products in the South African chemical industry is unknown as the industry is unwilling to share the required information. It is however known that big chemical companies do use imported titanium pipes and reactors (chemical processing) and that titanium sheets and mesh are also imported to produce products for electrochemical applications.

9.3.3. Technology (Where is South Africa now?)

South Africa imports the bulk of its intermediate and final titanium products used locally (limited number of parts machined from imported ingots). This result from the country not having a titanium melting facility to produce melted products and only a limited number of ingots are imported for further processing.

Two main technological paths are applied when further processing intermediate mill products or melted products. The first is processing intermediate mill products (or melted products) using the same technology applied in other metal processing industries (especially copper and stainless steel) (Roskill 2019). This is possible as the facilities that process titanium mill products are less stringent than titanium melting facilities, the main reason being the reduced working temperatures that lowers the risk of contamination. The second path is by importing specialised technologies that suit the specific product specification in titanium-only processing facilities. An example of this is the selection of either three, four of five axis computer numerically controlled machines to produce products from titanium rods.

9.3.4. Research and Development (Where is South Africa now?)

South Africa is dedicated to mill product R&D and several processes are being researched with the intention to be commercialised within the scope of the roadmap timeframe. Four research areas were discussed with interviewees and will be elaborated on. These research areas are investment casting, solid state welding, super plastic forming and powder consolidation.

Investment casting research in South Africa is focusing on establishing a platform capable of producing complex titanium castings ready for industrial applications (industry qualified). Currently there is only one vacuum casting facility at a science council in South Africa, and it is on pilot scale. The research is ready to be taken up by industry and therefore funding (and an industrial partner) is needed to build a larger industry scale vacuum melting facility. This is a promising technology for South Africa as it is a difficult technology to master and good local expertise have been developed.

Titanium can be joined using fusion welding, brazing, adhesives, diffusion bonding and fasteners. South Africa has focused its research on solid state welding. The aim of this research is to establish a platform to join titanium in South Africa. Solid state welding technology has been reported to be industry ready as fatigue tests on welding of 3 mm sheets have provided good results. Research on rotary friction welding of Ti-6Al-4V bars were successfully completed.

Super plastic forming is one of the main processes to produce NNS products. The NNS product is produced by incorporating diffusion bonding between two halves of a die and heating the material to a specific temperature. In the following step hot argon gas is pumped into the die at the pre-determined pressure to force the titanium to deform super plastically into the NNS set by the lower die (AZoM, 2004). This technology is available internationally, but the technology is too expensive and therefore local research is being conducted in this field to develop a new technique.

Developing this technology in South Africa will add value to the imported intermediate titanium mill products and produce a fabricated final mill product that can be sold for a higher price. Currently the development is looking at mechanical characterisation of the actual component.

Research on the production of mill products from titanium metal powder (powder consolidation) has also been conducted in South Africa. The main challenge experienced during this research was obtaining the appropriate feed material from international companies. The billet that was produced was too porous and further research will focus on improving the density to be more comparable to wrought products. This research is conducted in conjunction with the local research on titanium metal powder.

9.3.5. Resources (Where is South Africa now?)

South Africa does not have a melting facility and therefore does not produce titanium melted products required to produce titanium mill products. Limited amounts of melted products are imported for local processing. South Africa does not produce intermediate mill products locally and import it together with the bulk of the finished products. Interviewees reported the bulk of the imports were from the USA and China, depending on the quality and quantity needed.

As mentioned earlier, similar equipment and skills are required to produce titanium mill products compared to other metal products. This means that existing skills from the metal industry can be applied to the titanium industry. Interviewees confirmed that the same equipment can be used for different metals by stating that parts are not machined under vacuum, but that a lot of lubricant is required to reduce the temperature during machining of parts. No oxidation and quality reduction of titanium rods were observed during cutting of rods into shorter pieces reinforcing that similar working conditions can be applied compared to other metals.

9.4. Vision Element: Where does South Africa want to go?

The vision element for local mill product production (stage 6) is to expand on the local capacity and expertise to produce intermediate and final mill products for both the local and the export markets with the focus on medical, chemical and aerospace industries.

The bulk of the survey answers (73 %) agreed with the vision element for local mill product production. Although the survey agreed with the three main industries identified by the interviewees, the order of importance varied. The bulk of the survey answers indicated that the medical and chemical industries should be the focus for future mill product production and that developmental work should be conducted for the aerospace industry. This is a valid point as entering the aerospace industry as an OEM is challenging and takes several years. Building skills and expertise in the other two industries would ensure a profitable industry while establishing the capabilities for the aerospace industry.

9.5. How will South Africa get there?

According to the data collected from the interviews, the majority of the interviewed experts expect the local titanium mill product market to grow in the next three years (73 %) and continue to grow for the next 10 years (84 %). The reasons given by interviewees for the expected growth within the titanium mill product market are:

- producing niche mill products to export to the international market,
- the identification and establishment of new competitive markets,
- South Africa advancing part production for local use in the chemical industry,
- increased local capacity for production of local and global medical products,
- the growth within the global aerospace industry,
- increased accessibility to imported titanium ingots,
- an industry awareness on properties of titanium,
- a decline in titanium price as technologies and efficiency of titanium production improves,
- a local breakthrough in titanium metal production,
- a drive generated by government through local research institutions,
- aerospace contracts supported through government purchase agreements within the aerospace industry,
- OEM partnerships,
- a titanium mill product demand in Africa,
- driven by the import of sponge,
- the stabilisation of local politics linked to policies and incentives to promote the titanium industry, and
- the titanium mill product industry reaching maturity.

9.5.1. Market (How will South Africa get there?)

The titanium mill product industry is already established in South Africa and expected to grow along with local processing capabilities. As mentioned above the current market is driven by demand and the country's engineering capability in the medical, chemical and aerospace industry. One of the interview topics was asking for the experts to identify the preferred industries that would utilise titanium metal and the outcome is shown in Figure 38.

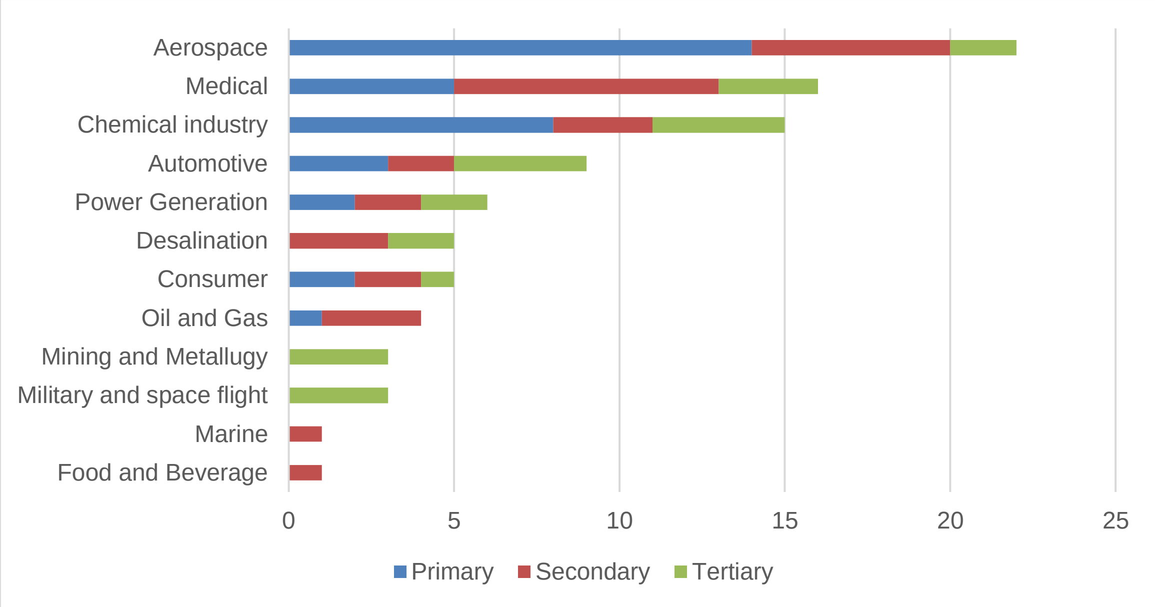


Figure 38. Primary, secondary and tertiary recommended industries that should utilise titanium metal locally. The number of hits per industry is presented on the x-axis.

During the interviews, each interviewee was asked to select a primary, secondary and tertiary preferred industry that South Africa should produce titanium metal for. The primary was their first option industry, the secondary their second option industry and the tertiary interviewees' third option industry. Based on Figure 38, South Africa should focus on producing titanium products for the aerospace, medical and chemical industries. Figure 38 only considers the interview answers. The top industries were confirmed during the survey, but the importance of the aerospace industry was indicated in third place instead of first place. Reasons for this could be related to the experts that participated in the survey acknowledging that the use of titanium within the local aerospace industry is still immature, the established success within the local medical industry and the low-quality requirement for the chemical industry making them better investment options with regards to this stage (mill product production) of the titanium metal value chain. Table 26 provides the main reasons supplied by the interviewees for selecting the top three industries.

Table 26. Reasons for selecting the top three industries for the local titanium industry.

Medical	Chemical	Aerospace
Titanium is biocompatible (titanium properties)	South Africa has an established chemical industry and titanium products can feed directly into this	Exclusive use is based on the properties of titanium
The use of titanium in the medical industry has a high profit margin (high value for low volume of products)	Once established the chemical industry would be able to supply high volumes of product that could be absorbed by the local industry	The existing demand (grow with ±5 % per year)
The South African private medical industry is highly developed with skilled doctors who drive innovative and exploratory methods	Processes could benefit from titanium parts, having less maintenance due to corrosion resistant properties (higher cost of the part could be justified with reduced maintenance cost and an improved product life span)	The spill-over effect of this industry is big and the multiplier effect large
An export market for titanium parts produced for the medical industry already exists for South Africa	Compatibility of the metal with the chloro-alkaline industry (titanium properties)	South Africa has an existing market for titanium within the aerospace industry
The South African medical industry is a well-established industry that already has the knowledge and capabilities for using titanium	Less stringent requirements compared to aerospace industry	This is a niche market and South Africa would be able to compete internationally if the correct quality product can be supplied
AM technology is a proven technology in South Africa especially within the medical industry	Money can be made back immediately while improving skills and capabilities for the aerospace industry	If a country can produce for this market, then rest of the industry is easy
	A link exists between the use of $TiCl_4$ to produce pigment and to produce titanium-metal, thus both markets exist in the chemical industry	The export focused market will benefit South Africa
		All the products have high value for a low volume of products
		The titanium powder market is also in the process of maturing which opens the AM industry more for Aerospace.

As mentioned in the global outlook section, the most widely imported mill products globally are sheet and plate (34 %), bars and rods (32 %), tubes and pipes (7 %)

and the remaining portion being any other form of mill product. Applications for these products within the identified industries in Table 26 should therefore be found and used to drive the local market.

Based on the low export figures displayed in Figure 37, South Africa needs to conduct market research and obtain the ideal product(s) to give it a bigger market share in global mill products. There is also the need for a drive from government to promote or incentivise the use of locally produced titanium parts to stimulate the industry. Interviewees highlighted that government needs to consider the titanium industries that are already operational in South Africa and that they need to be supported through incentives. A possible incentive that was mentioned was an export incentive. South Korea has a titanium mill product export incentive that reduces the cost of their products to the international market making their products more competitive. Interviewees mentioned that previously there was such a drive from government for the buying of value adding machines, but that this project has now expired.

9.5.2. Product (How will South Africa get there?)

From Section 9.3 “Where is South Africa now?” it is clear that a larger quantity of mill products are imported for local use compared for products produced for the export market. This section “How will South Africa get there?” should indicate a way for the country to expand on the local capability to produce intermediate and final mill products for both the local and the international markets (the vision element). For South Africa to be competitive in the global titanium mill product market it would have to supply low quantities of niche parts or high quantities of traditional parts at lower cost.

9.5.2.1. Mill Products Produced for the Local Market

Results from the expert interactions indicated that products that should be produced within the next decade should focus on medical, chemical and aerospace industries. Between the three mentioned industries the medical industry is the most mature. As this industry is already at a mature stage the focus (local and export) should remain on producing products for orthopaedic implants, dental applications, medical tools and equipment.

The chemical industry has not yet reached its potential within the local market. Although imported titanium mill products are being used in this industry, no mill products for this industry is known to be produced locally. Experts indicated that this should be addressed within the next decade by localising the production of parts used in the chemical industry. Based on the inputs from experts as well as secondary data, two possible routes could be taken for product production for the local chemical industry.

- The first option (Option A) is to focus on the production of niche high value parts used in the chemical industry such as valves or heat exchangers. Products would then be produced on small scale but sold at a higher cost. These parts could potentially be competitive within the global market (exports).
- The second option (Option B) is to produce parts for the already established local chemical industry such as bars, sheets, bolts, nuts and washers. Rods, tubes and pipes should also be considered as they have been identified as the most tradable products within the titanium industry. The production of products for option two requires simple and repeatable manufacturing techniques that will allow for large quantities of the products to be produced saving time and possibly money. The biggest risk for parts produced from the second option is global competitiveness. As indicated in the global outlook section large companies with extensive vertical integration on the titanium metal value chain have an inherent cost advantage and are therefore able to produce large quantities of these products for cheaper.

Selected South African companies have been aiming to produce products for the aerospace industry and have achieved this by producing non-critical parts. The production of products for this industry should be approached systematically by first gaining confidence and experience in the production of non-critical parts followed by critical parts. Critical parts could be entry level such as screws, bolts and fasteners or more advanced such as blades, disks, seals and engine parts. The aerospace industry has a lot of regulation that goes along with part production and this might delay the progress made within this industry. It should be noted that although South Africa has an aerospace industry it is limited and most of the parts produced for this industry would be exported.

9.5.3. Technology (How will South Africa get there?)

“Titanium can be fabricated into industrial components using the same equipment as stainless steel and copper” (Roskill, 2019). This statement is of high value for South Africa as the country already has an established stainless steel and copper industry indicating that the technology to produce titanium mill products is already available locally.

To date one of the key global industries driving titanium development is the aerospace industry. This industry complicates the statement made by Roskill that titanium can be processed in a stainless steel and copper workshop in that higher standards apply for producing parts for the aerospace industry. This study divides products produces within the aerospace industry into critical and non-critical parts. Technologies applied to produce critical parts have to ensure that they can achieve strict specifications. Technologies used to produce non-critical parts have a bit more leeway as interviewees indicated that limited machining of parts are conducted in general workshops.

The aerospace industry requires the application of strict specifications, which as a result limits the production runs. Each company within the aerospace industry does not only look at its unique specification, but also define a processing route (Total Materia, 2018). The result of this stringent aerospace processing system is that one aerospace company might buy the titanium product, but a different company might reject the product if a different processing route (technology) was used. To protect them against this, companies producing mill products for aerospace applications prefer to sign long-term contracts for titanium metal supply with primary metal producer (Van Vuuren, 2009b). Several of these companies have also adapted to only produce small batches of mill products that ensure that the required quantities of products are produced (Total Materia, 2018). What further limits producers is the fact that parts produced for the aerospace industry is expensive and it would not make economic sense to use the overqualified material for other less stringent, lower grade industries such as the chemical industry.

The medical industry has similar complications to the aerospace industry as the health regulations that might restrict the use of conventional metal workshops. Interviewees that produced medical mill products indicated that they have a titanium dedicated facility that produces both the required medical implant as well as tools and equipment.

Technologies to produce or further process titanium mill products for the non-critical aerospace industry, the medical as well as the chemical industries are already available in South Africa. These technologies are the same as that being used in other metal industries such as the stainless steel and copper industries. South Africa will also continue to import specialised machining equipment for dedicated engineering facilities. Three local technologies that are currently under R&D are expected to be commercialised within the next three years namely investment casting, solid state welding and super plastic forming. Powder consolidation technologies (also being researched locally) are only expected to be commercialised closer to the end of the 10 year roadmapping period.

9.5.4. Research and Development (How will South Africa get there?)

South Africa is actively doing research in the production of titanium mill products. Techno-economic analysis is required for any new technology developed within three to 10 years. Two such technologies that should become locally available within the next three years are investment casting, solid state welding and super plastic forming.

Powder consolidation R&D to produce mill products from titanium metal powder should also be continued in South Africa. R&D on powder consolidation is done by producing bars and sheets from powder while applying technologies such as direct powder rolling. This method should be considered if South Africa has a breakthrough in the business of producing cheap titanium metal powder. As this technology is researched in conjunction with the production of titanium metal powder the aim should be to commercialise this technology by the time powder is produced locally (towards the end of the 10 year roadmapping period). This commercialisation would be dependent on the feasibility of the use of locally produced powder to produce powder consolidated mill products.

9.5.5. Resources (How will South Africa get there?)

The feedstock to produce titanium mill products are melted products or titanium metal powder. South Africa is not expected to produce melted products within the next decade, but the country is expected to produce titanium metal powder towards the end of the 10 year roadmapping timeline. Other resources to consider is the readily available skills within the stainless steel and copper industries that can be applied in titanium mill product production. A knowledge base would also be built through the R&D from both stage 5 (melted products) and stage 6 that focus on vacuum processing of melted products.

9.6. Discussion: Roadmap for Titanium Mill Product Production

The results provided in this chapter (Chapter 9) discussed stage 6 of the South African titanium metal value chain (mill product production). Although this stage is established within the country, the bulk of the mill products used are imported indicating that the local production capabilities are small.

In order to produce a roadmap for the mill product stage of the titanium metal value chain the local industry was investigated using market, product, technology, R&D as well as resources as a guide. These are the roadmapping layers as recommended by the generic technology roadmap layout and was applied to the existing South African titanium mill product industry by considering “Where is South Africa now?”, “Where does South Africa want to go?” and “How will South Africa get there?”. The results obtained from investigating the roadmap layers are summarised in Table 27.

Table 27. Summary of titanium mill product production (stage 6).

Where is SA now?	Market	• South Africa has an established, but small mill product market • The bulk of the mill products used and processed locally are imported (in 2018 246 t of mill products were imported and 47 t exported) • Industries that have produced mill products locally are aerospace and medical • The local chemical market is dependent on imports
	Product	• A limited number of local companies produce titanium mill product • The top mill products being imported are bars, sheets, bolts, nuts and washers • Medical industry: o Orthopaedic implants, dental implants, medical tools and medical equipment • Aerospace industry o Non-critical parts • Chemical industry o Little is known on the detailed use of titanium within the local chemical industry, but the use of titanium pipes and sheets have been reported
	Technology	• Imported final mill products require no additional processing • Processing occurs using the same technology/workshop as other metal industries (e.g. stainless steel and copper industries). This is either on imported intermediate mill products and/or locally produced mill products from imported melted products • Dedicated engineering facilities import machining equipment based on product specification. This is either on imported intermediate mill products and/or locally produced mill products from imported melted products
	R&D	• South Africa is dedicated to research on mill product production and four of the leading research areas are: o Investment casting o Solid state welding o Super plastic forming o Powder consolidation o Market research to confirm global mill product need and industry competitiveness
	Resources	• Existing processing skills from mill product production within the existing metal industry can be applied to the titanium industry (stainless steel and copper industry especially) • Skills obtained from working under vacuum conditions are obtained from the R&D conducted in the previous stage of the titanium metal value chain (stage 5, melted products) • South Africa has access to relatively cheap electricity • The addition of renewable energy sources to the local energy mix

Where does SA want to go?	Vision element	*The vision element for local mill product production (stage 6) is to expand on the local capacity and expertise to produce intermediate and final mill products for both the local and the export markets with the focus on medical, chemical and aerospace industries*
How will SA get there?	Market	• The market for titanium mill products is expected grow within the next decade as the local machining/processing capabilities grow • The biggest market for titanium mill products produced in South Africa will be within the aerospace, medical and chemical industries
	Product	• Aerospace industry: ○ South Africa is already producing non-critical parts for the aerospace industry. This is for both the local and export market ○ It is expected that South Africa should start producing entry level critical parts such as screws, bolts and fasteners within the next three years ○ If South Africa can comply with international standard the country could be producing advanced critical parts for the aerospace industry within the next decade. These parts would be exported (blades, disks, seals and engine parts) • Medical industry ○ Mill product production is at a mature stage in South Africa and for the next decade the country should continue producing orthopaedic implants, dental implants, medical tools and medical equipment • Chemical industry ○ Import bars, sheets, bolts, nuts and washers ○ Option A: South Africa should produce niche products for the chemical industry ○ Option B: South Africa should produce titanium mill products already used locally such as bars, sheets, bolts, nuts and washers
	Technology	• Processing occurs using the same technology/workshop as other metal industries (e.g. stainless steel and copper industries). This is either on imported intermediate mill products and/or locally produced mill products from imported melted products • Dedicated engineering facilities import machining equipment based on product specification. This is either on imported intermediate mill products and/or locally produced mill products from imported melted products • The commercialisation of novel local technologies: ○ Investment casting (3 years) ○ Solid state welding (3 years) ○ Super plastic forming (3 years) • Powder consolidation (10 years)
	R&D	• Continues R&D on technologies being developed ○ Investment casting ○ Solid-state welding

		○ Super plastic forming ○ Powder consolidation • Techno-economic studies should be conducted on all of the technologies being researched to determine the feasibility within the local and global titanium metal industry • Market research to confirm global mill product need and industry competitiveness
	Resources	• Skills obtained though processing metal within the existing metal industry can be applied to the titanium industry • Skills and experience obtained from R&D focusing on VAR technology (from stage 5, titanium melted products) can be applied to this stage as a resource. • Relatively cheap electricity • Increase in renewable energy

The summary presented in Table 27 indicates the current stance, the future vision element and discusses methods on how this future vision element can be achieved. This information was used to produce a roadmap for the mill product production stage of the local value chain. This roadmap was designed to cover a 10 year period (2021 until 2030) while considering the progress in medium-term (three years) and long-term (an additional seven years). The roadmap is displayed in Figure 39. The asterisk "*" in the figure indicates that powder consolidation will again be discussed in another roadmap in Figure 46 (stage 8, powder product production) showing a division between these two value chain stages.

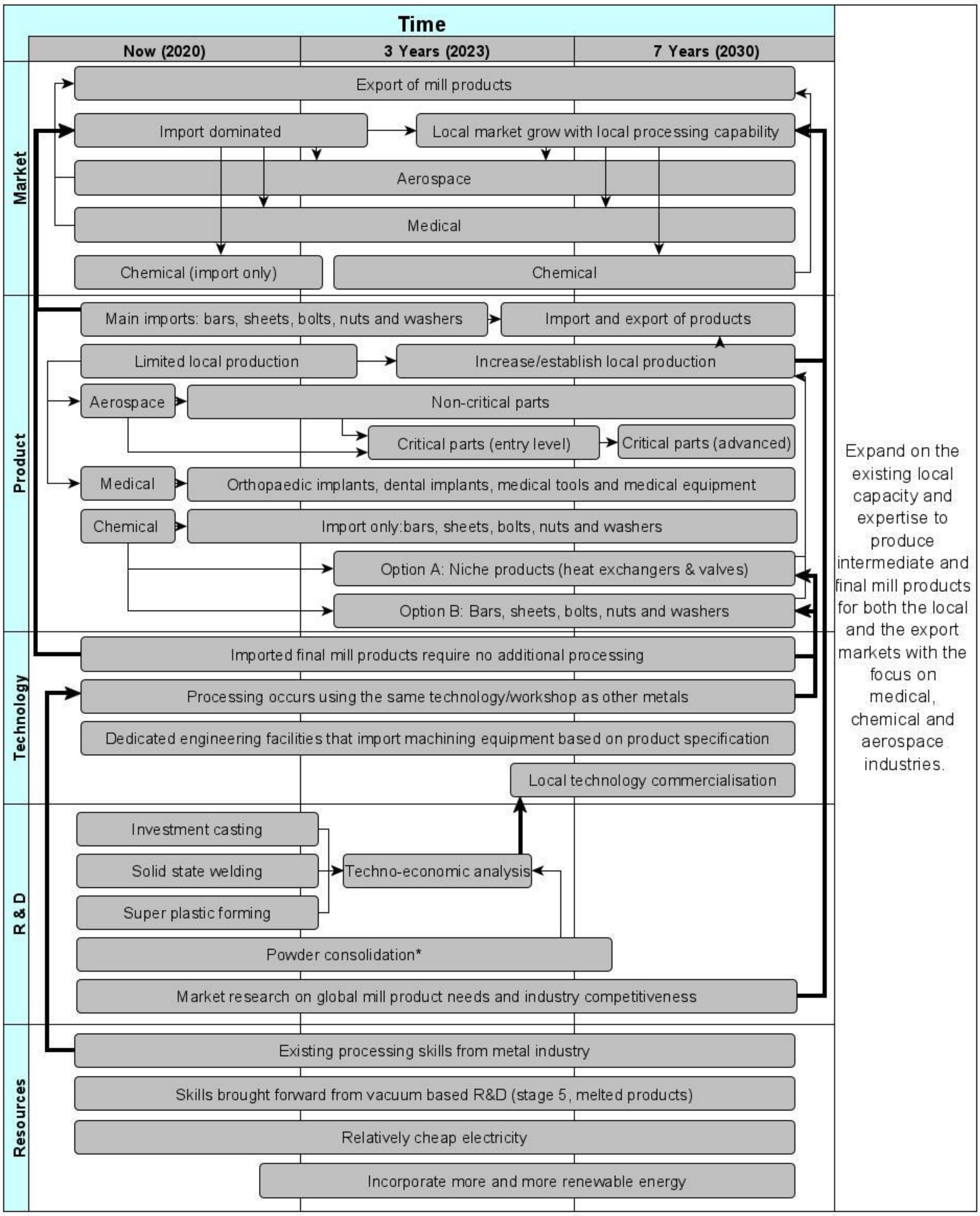


Figure 39. The local 10 year roadmap for titanium mill product production (stage 6). Powder consolidation* uses powder as a feedstock not melted products.

The first layer of the roadmap indicates the market. The bulk of the titanium mill products are imported either as finished (does not require any additional machining or fabrication) or intermediate (processed into a shape that can be used as is or the part must be further machined or fabricated) mill products. Although South Africa imports both final and intermediate mill products, the country also produces limited amounts of mill products from imported ingots. The markets that consume the bulk of the imported mill products are the aerospace, medical and chemical industries. Although the local titanium mill product market is small (imported only 246 t in 2018) it is expected that the market will grow together with the local mill product processing capability.

The next layer on the roadmap indicates products from the mill product value chain stage. As this industry is currently dominated by imports the bulk of the mill products available in South Africa are bars, sheets, bolts, nuts and washers. As indicated in the market section these products are mainly distributed to the aerospace, medical and chemical industries. Local capabilities for mill product production is centred around the medical and aerospace industry with no available information on any local mill products produced for the chemical industry. Products for each of the three markets are discussed in the bullets below.

- The local medical industry is mature and already producing world class mill products from titanium metal. The main medical products produced globally as well as in South Africa are orthopaedic implants, dental implants, medical tools and medical equipment. South Africa should ensure that its capabilities and innovation within this industry remains competitive with the global market.
- The local aerospace industry is currently focusing on the production of non-critical parts, but the results obtained from this study indicates that South Africa should start production entry level critical parts (such as bolts, screws and fasteners) within the next three years. The results also indicated that as production experience grows within the aerospace field, South Africa should aim to produce more advanced critical parts such as blades, disks, seals and engine parts. It should however be noted that the aerospace industry is strict, and it takes time to qualify parts. This might cause a delay for the local production of critical parts for the aerospace industry.
- The use of titanium within the local chemical industry is the least developed between the three identified industries. Parts currently being used within the chemical industry (all imported) are bars, sheets, bolts and washers. Two options are presented on the roadmap for the local production of parts for the chemical industry. The first is the production of niche products such as heat exchangers and valves. The second is the production of cheaper intermediate mill products such as bars, sheets, bolts, nuts and washers. The first option (niche products) would produce products that could be sold at a higher cost compared to the bars, sheets, bolts, nuts and washers proposed by the second option. The capability to produce these products locally should be developed within the next three years. The focus should initially be on the local market, but the export market should also be considered if feasible.

The imported final titanium mill products require no additional processing and it is absorbed directly by the selected industry. Mill product producers report that they either apply the same technology used for processing other metals (such as copper and stainless steel) when processing titanium mill products or use specialised technologies within dedicated engineering facilities. The bulk of the specialised technologies are imported with the required machining specifications. It is expected that within the next decade South Africa will be commercialising locally designed technologies to advance local mill product production.

The top four R&D areas investigated for this study were investment casting, solid state welding, super plastic forming as well as powder consolidation. R&D on these technologies will continue over the next decade. A need has been identified for techno-economic assessment to be conducted on each of these technologies to determine whether it is feasible to be commercialised. In addition to the techno-economics the need for a more generalised market study on the production of mill products in respect to global competitiveness has also been identified. This would indicate whether the production of final mill products locally is more economic compared to importing the same product (e.g. from China). This study should also substantiate the proposed products for the next decade identified for the aerospace, medical and chemical industries.

When considering resources in this study three main subgroups were mainly considered. The first is raw materials/feedstock. South Africa does not produce the precursor to titanium mill products which is titanium melted products. The second resource is human capital. Results from this study indicate that the same equipment can be used to process titanium mill product and other metals such as copper and stainless steel. This means that except for the skills already developed within the small local titanium mill product industry, additional skills already exist within other metal industries that could be transferred to the titanium industry if needed. The third resource is electricity. South Africa’s electricity is currently relatively cheap compared to developed countries. This might be a driver to for industrial development, but the country is currently experiencing an electricity supply crisis that is rather obstructing industry development. The South African government is working toward creating a more stable energy supply and the results of this should be observed within the next decade.

9.7. Chapter Summary

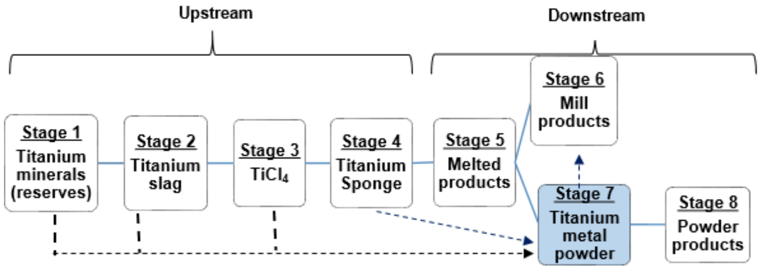
Chapter 9 presents the results obtained during this study on titanium mill product production (stage 6 of the titanium metal value chain). The mill product stage of the titanium metal value chain is one of four established stages within the South African titanium metal value chain. In the chapter literature review section, the processes used for mill product production were elaborated on. The two main processes discussed were wroughting and casting.

The global outlook on mill product production indicated that countries that have access to all or most of the precursor value chain stages have an economic advantage above countries that do not. This allows major producers to capitalise on downstream value addition with reduced input costs as process streams could complement each other. Despite the mentioned advantage that major producers has, the trade of mill products is large and geographically diverse. This creates an opportunity for smaller mill product producers (such as South Africa) to access the global market with a specific product that is not in direct competition with the larger producers (a niche market).

The local markets identified for mill products are the aerospace, medical and chemical industry and it is expected that these will remain the main markets over the next decade. It is also expected that the usage of locally produced mill products for these markets will grow. Products produced for the medical industry within the next decade are expected to remain the same or similar. These are orthopaedic implants, dental implants, medical tools and medical equipment. Product evolution is expected especially within the aerospace industry. The South African aerospace industry is currently producing non-critical parts and this should be evolved to entry level critical parts within the next three years and as the local capabilities grow advanced critical parts could be produced within the next decade. No parts are produced for the chemical locally (imports of all titanium parts). The results indicated that South Africa should start producing parts for the chemical industry within the next three years.

South Africa is still in the process of expanding on its mill product industry. Mill products are imported as final products or as intermediate products that will be fabricated into final components locally. One of the key opportunities discussed in Chapter 9 is that the processing of mill products does not necessarily require vacuum applied machinery and that processing can be done in the same facilities as copper and stainless steel. The results indicated that South Africa should focus on developing the production of mill products especially for the aerospace, medical and chemical industries. The country is also investing in several R&D efforts to ensure that the technologies applied locally are competitive on not only a local scale, but also globally.

10. Chapter 10: Stage 7 (Titanium Metal Powder Production)



10.1. Literature Review

Powder metallurgy (PM) is the term used for a highly developed method of manufacturing to produce ferrous and non-ferrous parts (EPMA, 2018). PM includes the production of powders, the compaction and shaping of powders, sintering of powders as well as post sintering processes that are used to fabricate ready-to-use components (Fang *et al*., 2017). Chapter 10 and Chapter 11 will both cover PM with Chapter 10 focusing on the powder production part and Chapter 11 on powder processing.

10.1.1. Titanium Metal Powder

Titanium has attractive properties in many different markets, but the cost of producing mill products is highly unattractive. This conundrum has been studied for years and dedicated research is seeking a method to produce cheaper titanium metal products. The direct production of titanium metal powder has been identified as a viable way to reduce the high production cost of titanium products (Bolzoni, Ruiz-Navas and Gordo, 2017). This proposed cost reduction can be attributed to two main aspects. The first aspect is by the direct reduction of titanium mineral concentrates or an intermediate precursor ($TiCl_4$) to form titanium metal powder (Roskill reports, 2013). The second aspect is related to a reduced cost for processing and manufacturing of the titanium product by powder metallurgy compared to the conventional metallurgical route (Bolzoni, Ruiz-Navas and Gordo, 2017). Both cost saving opportunities are displayed in Figure 40.

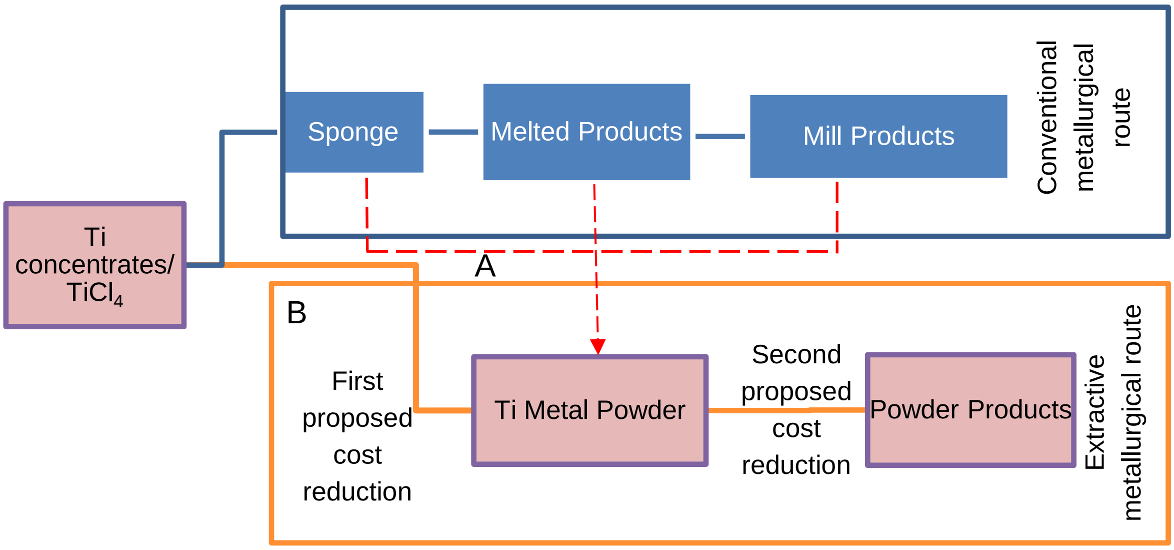


Figure 40. An illustration of the two main cost reduction aspects for considering the powder metallurgical route (orange) above the conventional metallurgical route (blue).

There are two general routes used to produce titanium metal powder. The first and most common route ("A" in Figure 40) is via the conventional metallurgical route. From here sponge, melted products or mill products are further processed to a powder. The second route (B in Figure 40) produces titanium powder by direct powder production also referred to as the product of extractive metallurgical processes (Fang *et al*., 2017; Roskill reports, 2013).

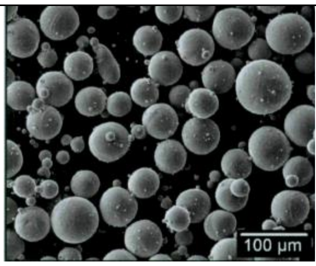
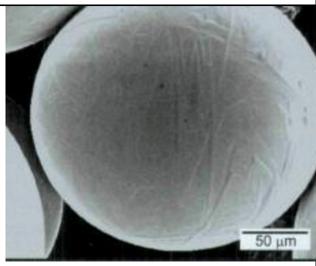
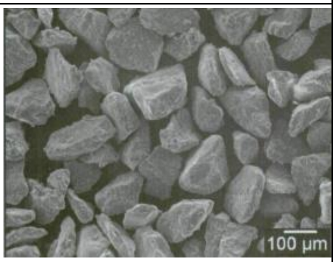
Powder comes in several sizes, shapes and qualities all of which have an important role to play in PM. Each production process has an influence of each of these parameters and indirectly an influence on the cost of the powder. These three parameters are part of standard powder metallurgy and will therefore not be discussed in detail within the thesis.

10.1.2. Powders from Sponge, Ingot, Mill Products or Scrap

Powders produced as a by-product during the production of titanium sponge are called sponge fines (McCracken, Motchenbacher and Barbis, 2010). These sponge fines have irregular morphologies and are generally smaller than 150 µm (Henriques, Sandim and Da Silva, 2003). They are collected through sponge screening and can then be directly applied to some of the conventional bulk PM processes such as press-and-sintering and/or cold isostatic pressing (CIP)/sintering to produce plates and billets (powder consolidation for mill product production). The plates and billets could then be used to produce sheets, bars and tubes by means of conventional metallurgy (McCracken *et al.,* 2010). The type of end product aimed for is dependent on the quality of the source titanium used. Without treatment, sponge fines (from the Kroll and Hunter processes) still contain metallic salt residues which could lead to incomplete densification of the final product as they become gaseous and form porosities (McCracken *et al.,* 2010; Henriques, Sandim and Da Silva, 2003).

Except for the fines produced during sponge production, titanium metal powders can be produced by further crushing and milling of melted products, mill products and titanium scrap. The most common processes used to produce titanium powder from the mentioned mill titanium are HDH, gas atomisation and plasma-rotating electrode process (PREP) (Oh et al., 2014). Table 28 provides more information on each of these processes.

Table 28. Common processes for making powder from titanium sponge, melted products, mill products or scrap (Source: McCracken *et al.*, 2010).

	Gas atomisation	Plasma-rotating electrode (PREP)	Hydrogenation-dehydrogenation (HDH)
Powder shape	Spherical	Spherical	Angular to sub-angular
Powder particle size distribution (PSD)	50-300 µm	100-300 µm	150-300 µm 45-150 µm <45 µm
Process summary	Titanium feedstock is formed into an electrode which is heated until liquid titanium falls through the induction coil and is atomised within argon gas. The electrode rotates slowly to ensure even melting and a continuous stream of liquid titanium is ensured by lowering the titanium electrode slowly into the induction coil	A transferred arc plasma torch acts as a heat source. The feedstock is a raw material high purity electrode bar. An argon or helium plasma melts one end of the anode which rotates causing molten droplets to undergo centrifugal acceleration away from the anode as spheres	Titanium is heated above 350 °C and cooled in excess hydrogen. Different titanium phases are formed, come more brittle than others making crushing and milling possible. The material is then dehydrided under vacuum at 750 °C to liberate the hydrogen and convert back to titanium metal. HDH is done to allow for milling and crushing of hard titanium sponge.
Visual			

From Table 28 it is clear that titanium metal powders are produced in different shapes and sizes depending on the process selected to produce the powder. The powder shape and size is important, as a spherical powder will have better packing and flowing properties, which are preferred for further processing of titanium powders (McCracken *et al.,* 2010).

The HDH process for producing titanium powder is one of the most popular processes as it has a low cost compared to atomised powder production (Fang *et al.,* 2017). This process is especially useful as it allows hard sponge to be broken down into powders. This embrittlement method produces powders with a reduced particle size distribution compared to titanium sponge fines. The benefit with a smaller range of particle sizes is that more methods are available to consolidate the powders. These methods include near-shape methods such as HIP, direct powder rolling and vacuum plasma spraying (VPS) (McCracken *et al.*, 2010). The process of HDH can be applied to produce titanium powder from sponge, melted products, mill products and titanium scrap after crushing and/or grinding (Fang *et al*., 2017; McCracken *et al.,* 2010).

The reason for producing titanium metal powder from sponge, melted products or mill products rather than producing conventional titanium mill products is related to the economics (see the dotted red line on Figure 40). Traditional casting and forging operations are expensive and large quantities of titanium losses (buy-to-fly ratio) are experienced along the processing chain (Goso and Kale, 2011; Roskill reports, 2013). This cost can be countered through the production of NNS products which include castings and products produced from titanium metal powders (Fang *et al*., 2017).

10.1.3. Powders from Direct Powder Production

This is also referred to as powder from the extractive metallurgical process. Titanium researchers have been focusing on powder metallurgy (PM) for more than four decades (Fang *et al*., 2017) trying to create a direct process that can compete or replace the conventional metallo-thermic reduction processes (such as the Kroll process). The latest research has focused on chemical and electrolytic methods with the aim to produce titanium powder directly without producing sponge. From this research several successful processes have been developed, but none has come close to replacing the Kroll process (Roskill reports, 2013). Table 29 indicates the top powder metallurgy processes for titanium as well as their progress.

Table 29. Research conducted on titanium metal powder production (Source: Doblin, Freeman and Richards, 2013; Osypenko, 2015; Roskill, 2019; Balinski, 2015; Jackson, 2019).

Process	Country	Progress
Armstrong metallo-thermic process	USA	• The largest single facility titanium powder production capacity is in the USA at Cristal Metals' Armstrong facility (opened in 2013). • Production capacity for 1800 tonnes of angular titanium metal powder using $TiCl_4$ as the feedstock. • In addition to the combined HDH process capacity it is the second most important producer of angular titanium metal powder.
FFC Cambridge electrolytic process developed by Metalysis	UK	• Process is being commercialised by Metalysis. • This process produces titanium powder directly from rutile or pure TiO_2 in a single step. • Metalysis was placed under administration in mid-2019 but was secured by a buyer later in that year. • The FFC process is in its "Generation 4" powder production stage and is one step away from being able to produce a selected range of powders on commercial scale. • The FFC process is said to be more efficient and environmentally friendly than its competitors. • There is still an ongoing debate on whether this technology would be able to produce titanium metal powder commercially at a competitive cost.
CSIRO.TiRO process It is based on the continuous reduction of $TiCl_4$ to titanium powder with Mg in a fluidised bed	Australia	• The TiRO process is being commercialised by Coogee Chemicals. • In 2019 the company successfully commercialised a 200 tpa titanium alloy powder production facility. This is in addition to its existing 50 tpa pilot plant (Roskill, 2019). • This is a two-stage process. In the first stage $TiCl_4$ is reacted with magnesium powder in a fluidised bed. This forms a solid magnesium that contains dispersed titanium particles of micron size. In the second stage continuous vacuum distillation is applied to separate the magnesium chloride from the friable titanium. • This facility uses the same chemistry as the Kroll process but runs on a continuous scale instead of batch and produces a powder product instead of sponge.

As mentioned, no process has been developed that can directly compete with the conventional Kroll process to produce titanium metal. This means that there is still a big opportunity for development and several countries are actively taking part in researching alternative methods (chemical and electrolytic) to produce titanium metal powder. Countries taking part in this type of research are the USA, Japan, South Africa, Australia, the UK, Germany, Canada and Italy. Some of the promising technologies are listed.

- South Africa with the CSIR-Ti process (Whittaker, 2012). The aim of producing titanium metal from $TiCl_4$.
- Japan with the development of the Preform Reduction process. The Ono-Suzuki process is a variation of this process (also by Japan) (Okabe, Oda and Mitsuda, 2004). The production of titanium metal from TiO_2.
- The UK (Cambridge University) with the Chinuka process. Titanium metal is produced from natural rutile.
- The USA with the Materials & Electrochemical Research (MER) process. Titanium metal is produced from $TiCl_4$ (Roskill reports, 2013).
- Norway with the development by Norsk Titanium. Titanium metal is produced from titanium oxide feedstock (Roskill reports, 2013).

Currently the main commercial processes for titanium metal powder production are the Armstrong and the HDH process (Roskill, 2019). An additional breakthrough in the direct production of a suitable and cheaper powder will have enormous economic implications.

Spherical powders are more desirable and therefore the plasma spheroidisation was developed to produce spherical powder from irregular powder. This has been successfully demonstrated on HDH powders (Roskill, 2019). Another method to obtain a more spherical powder from irregular powder is by mechanically blending or shearing angular powder to remove sharp edges. Although this technique does improve on the powder's flow ability it cannot be classified as spherical.

10.2. Global Outlook: Titanium Powder Production

The 2019 Roskill report estimated a titanium powder capacity of 15 ktpa for the same year. For 2019, this is approximately 4 to 7 % of the estimated capacity for titanium metal product production (only mill products plus powder products). The makeup of the capacity is shared mainly by angular powders and to a lesser extent spherical powder. The 2019 Roskill report also stated a conservative utilisation capacity for the two types of powder of 35 % for angular powders (3.4 kt estimated for 2019) and 25 % for spherical powders (1.4 kt estimated for 2019) (Roskill, 2019). The reason for the low utilisation estimations were not specified.

The bulk of the angular powders are HDH powders and are mainly produced in China and in Russia. The leading producer of angular powder through a chemical process (metallothermic) is Cristal Metal's facility in the USA using the Armstrong process. The largest producer of spherical titanium powders is Canada followed by the USA, France and the UK.

Titanium powder production is reported in nine countries namely Australia, Canada, China, France, Germany, Japan, Russia, UK and the USA. This picture looks different to the conventional Kroll route to produce titanium metal as powder is also produced in the southern hemisphere (Australia). This is important to note as having an alternative supply of titanium powder (now from the Southern hemisphere) could be beneficial to South Africa in terms of competing with prices from the Northern hemisphere.

The application of the HDH angular titanium powder production route offers an alternative to re-melting low-cost sponge or titanium scrap. This angular titanium powder can then be processed using pressing and sintering or direct powder rolling to produce a standard mill product such as a billets, plates or sheets. This can then follow the same processing steps as conventional mill products (Roskill, 2019).

The 2019 Roskill report anticipated that less than half a percentage of titanium metal circulated in the 2019 market would be produced through direct processes such as chemical (metallothermic), electrochemical and atomisation. Approximately 3 % of the market would be powders produced from sponge. The titanium circulation (expected at the time of publication) for 2019 is displayed in Figure 41 and includes powder, sponge and scrap circulation. Titanium powder production is presented in orange, sponge production in grey and scrap production by the three shades of blue.

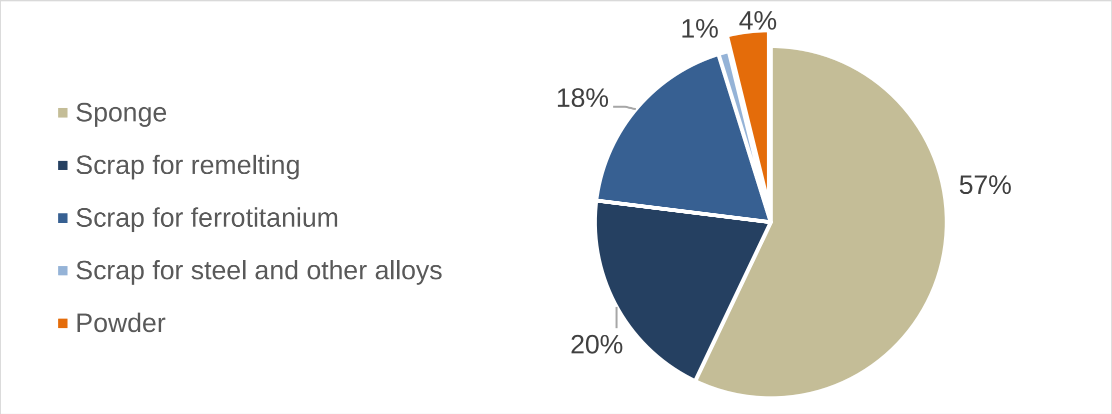


Figure 41. Titanium circulation for 2019 in ktpa. (Adapted from: Roskill, 2019).

From Figure 41, approximately 4 % of the global titanium circulation expected for 2019 is in the form of titanium metal powder. The bulk of this trade originates from the traditional sponge processing route for titanium metal production. Except for the Armstrong process no other commercial process for the direct production of titanium metal powder was reported in the 2019 Roskill report. It should be noted that Coogee Chemical from Australia did start producing titanium metal powder in the same year, but it is assumed that the Roskill report was compiled before this was confirmed.

The 2019 Roskill report did not report the price for titanium powder, therefore an older source "Global Titanium Powder Market Report 2017" was used to obtain this price. According to this report the price for titanium metal powder (in 2016) varied from US$ 99.3/kg to US$ 261.4/kg. The lowest cost powder was produced in China through the HDH process and the most expensive powder in Europe through a gas atomisation process (QY Research Group, 2017). Table 30 indicates the average prices of titanium powder produced using different techniques.

Table 30. The average global titanium powder prices from cheapest to the most expensive (Adapted from: QY Research Group, 2017).

Powder type	Average cost (US $/kg)
HDH (from China)	100
Armstrong	203
HDH + spheroidisation	210
Atomised	216
HDH (from Europe, Japan and USA)	217
Metalysis	229

According to Table 30, the cheapest powders were produced using the HDH process by China who is known to produce low-grade Kroll sponge. These powders would not be suitable for the aerospace industry. Except for the low-grade powders produced in China the average cost for titanium powder is above US$ 200/kg. It should be noted that the reported prices do not include trader increases. According to Simpson (2018) the cost of titanium powders from AM machines original equipment manufacturers (OEMs) is higher at US$ 300-600/kg.

10.3. Where is South Africa now?

South Africa does not produce titanium metal powder on commercial scale. Although the production of titanium metal powder is being researched, stage 7 of the titanium metal value chain is not yet established locally.

10.3.1. Market (Where is South Africa now?)

The market for titanium metal powder is driven by a need for parts produced using NNS processes such as AM and MIM. AM is a fast growing industry displaying an approximate growth of 14.4 % pa (Reports&Data, 2019). Locally the market for titanium metal powder is immature with only a few private companies having the ability to process titanium metal powder and the bulk of the country's ability based at research institutions.

In the South African Additive Manufacturing Strategy (RAPDASA, 2016), it was reported that the local AM industry is growing rapidly since 2013. The most advanced titanium AM projects locally is the Aeroswift project hosted at the CSIR National Laser Centre (NLC) as well as projects completed at the Central University of Technology (CUT) Centre for Rapid Prototyping and Manufacturing (CRPM) (RAPDASA, 2016). These will be discussed in more detail in Chapter 11 under titanium powder products.

To date the local market for titanium powder products is dominated by the medical, aerospace and leisure industries. Parts produced for these industries have most potential for opening a new market demand, but over time the technology is maturing and the applications for AM is getting wider. One of the drivers for the increased utilisation of powders is the decreasing cost of machines as well as materials (Cambell, 2018).

Annual import figures for titanium into South Africa were sourced from the Quantec/SARS database. The general search code for titanium is H8108 and was used to obtain trade data for “Trade data and articles thereof, including waste and scrap”. Three sub-headings were reported namely “*unwrought titanium and powders*”, “*waste and scrap*” as well as “*other”.* Titanium powder production (stage 7 of the titanium metal value chain) falls under “*unwrought titanium and powders*” that has already been mentioned in Chapter 8. Table 31 indicates the imports of unwrought titanium and powders for 2014 until 2018.

Table 31. Unwrought titanium and titanium powder imports into South Africa (Adapted from: QuantecEasyData, 2019).

Year	Mass in kg	Cost in ZAR (R)
2014	1 045	3 585 316
2015	4 048	1 878 732
2016	19 474	3 378 869
2017	2 187	3 514 826
2018	2 023	4 208 164

*The 2018 average rand to dollar exchange rate from Nedbank was used @13.25 (Nedbank, 2019)

Unfortunately, titanium metal powder import data is not reported as a separate entity but together with unwrought titanium. From the data (displayed in Table 31) it is observed that far less than 2 023 kg (2.02 t) of titanium metal powder was imported into South Africa in 2018 as the market data is combined shared with unwrought titanium. This indicates that the current local market for titanium metal powder is small.

Mill product production is still dominating the titanium metal industry and will do so for some time. Titanium powder production on the other hand is dominating in small niche markets and the demand is steadily growing especially in the aerospace, medical and leisure industries.

10.3.2. Product (Where is South Africa now?)

South Africa does not produce titanium metal powder on a commercial scale. Spherical aerospace grade Ti-6Al-4V titanium powder is mainly imported from Germany and Canada (although interviewees indicate that they have an extended list of 10-15 suppliers). Spongy, angular powders are mainly imported from China for research purposes.

10.3.3. Technology (Where is South Africa now?)

Locally no commercial powder production technology or powder spheroidisation technology exists. The drive to lower the titanium product cost has promoted innovation in ingot-based technologies. Technologies that can compete with titanium powder prices, in some cases, are investment casting, extrusion, hearth melting, water jet and wire electrical discharge machining (EDM). This competition is also driving PM research towards a more cost-effective production process.

10.3.4. Research and Development (Where is South Africa now?)

For just over a decade South Africa has been promoting research in titanium metal powder production and in 2013 the CSIR-Ti pilot plant was launched. This plant aims to develop a local technology (the CSIR-Ti process) to produce titanium metal powder through metallothermic reduction of $TiCl_4$. This program falls under the Advanced Materials Initiative (AMI). Since the launch of the CSIR-Ti pilot plant in 2013, research has focused on the direct metallothermic reduction of $TiCl_4$ in a liquid salt (CSIR-Ti process). According to the CSIR's website research has been conducted in both a continuous and more recently a semi-batch pilot processing plant. This research is still in the development stage of titanium metal powder production and pilot testing is still ongoing (CSIR, 2019a, 2019b).

Interviewees reported on the successful spheroidisation of the locally produced titanium powders (from the CSIR-Ti process) as well as from imported sponge fines. Both CP and titanium alloy powders have been successfully spheroidised locally. Local spheroidisation has been conducted using the Tekna spheroidisation machine imported from Tekna Plasma Systems Incorporated in Canada, but this has been done on small batch scale processing approximately 2 kg of powder per hour.

Research on HDH powder production has also been conducted in the past. The aim of this research was to produce fine titanium powders from imported titanium sponge. The produced powders were analysed, qualified and the results indicated that the preliminary research was successful.

10.3.5. Resources (Where is South Africa now?)

South Africa does not produce $TiCl_4$ as feedstock for titanium metal production. The continuous research conducted locally (CSIR-Ti process) utilises $TiCl_4$ that is mainly imported from China. As mentioned in Chapter 5, South Africa has an abundant resource of both rutile and upgraded ilmenite slag. Earlier in this chapter it was mentioned that some global processes (such as the FFC process) use these raw materials as feedstock for direct powder production instead of $TiCl_4$. If this technology or a similar technology were to be applied locally South Africa would have enough raw feedstock. This research has also laid a foundation for human capital development related to titanium metal powder production.

10.4. Vision Element: Where does South Africa want to go?

The vision element for local titanium metal powder production is to have access to powder production technology by 2030 and to be able to satisfy the local titanium metal powder demand with additional powder export capability.

The majority (71 %) of the survey answers agreed with the vision element for local titanium metal powder production. The main emphasis of this stage is the acquisition of powder production technology. The options obtained from both data collection sections (surveys and interviews) indicate three main technology route options:

- a breakthrough in local direct powder production technology,
- importing existing powder production technology, or
- importing ingots/electrode for local spheroidisation or atomisation (CP or alloys).

However, some views did not agree with the vision element. The first stated that a 10 year period is too optimistic to achieve this vision element. The second indicated that novel local technology should not be considered as this would require more than 10 years to commercialise but indicated that importing existing powder production technology could be achieved in the timeframe. A third opinion indicated that a local titanium powder plant is not economically attractive enough for industrial investment and that it is unlikely that the establishment of a new, lower cost technology would change this. This is attributed to the local powder production process producing CP grade angular powders that would still need to be alloyed and spheroidised. After producing the required powder, the cost would not be able to compete with the more attractive powder production routes of powder from sponge or ingots and applying plasma or induction atomisation.

10.5. How will South Africa get there?

South Africa has been investing in the development of the local titanium metal value chain, but as displayed in Figure 12 the country is missing several stages of this value chain. This value chain could be grown from both an upstream and a downstream side but overall, the main barrier is the actual production of the titanium metal. This refers specifically to stage 4 (sponge production) and stage 7 (powder production). As mentioned in Chapter 7, sponge production is expensive, there is a global over-supply and the process is energy intensive, therefore titanium metal powder production (through the electrothermal route) might be the better alternative.

Results obtained from the interviews indicated that most of the interviewees (86 %) do not expect a titanium metal powder plant within South Africa in the next three years. Results for the 10 year vision element indicated that only 36 % of the interviewees said that South Africa should not be producing titanium metal powder. Reasons (given by the interviewees) for South Africa not having the capability to produce titanium metal powder are given below from most to least important. These reasons were ranked during the survey section of the research.

1. Research on titanium metal production is progressing too slow and is scaling down instead of scaling up.
2. The process is complex and is still in a development stage.
3. South Africa should not compete in the global race to create a cheaper titanium production process as there are too many countries attempting this and all are much better funded than South Africa.
4. The unreliable South African electricity supply is generating economic instability and costing companies' money. Powder production technology is electricity intensive.
5. There is too much interference with research that is slowing down the rate of the process (e.g. procurement, funding and politics).
6. South Africa does not have the required resources such as skills and funding.

Approximately 64 % of interviewees indicated that they believe that South Africa will be producing titanium metal powder locally within the next 10 years. This is a major jump from the mere 14 % of interviewees who indicated that it could be possible for South Africa to produce titanium metal powder through a direct chemical (metallothermic) process in three years. Explanations provided by the interviewees for having a local powder production facility is:

- a breakthrough within local research that will attract funding and resources,
- with the aid of government, a committed industrial partner should be obtained,
- partnering up with international companies to import existing titanium metal powder technology (e.g. the Armstrong process, the FFC Cambridge process or the TiRO process). This would be dependent on a suitable value proposition for South Africa.
- South Africa importing atomisation or spheroidisation technologies and establishing a powder production facility that utilises the technologies,
- if a titanium metal powder production pilot plant could be established in three years, then a semi-commercial powder plant (direct production) would be constructed in 10 years (±500 tpa), and
- South Africa would have established skills in AM technology and would be able to produce locally value-added products for both the local and the export market, pending market demand.

10.5.1. Market (How will South Africa get there?)

Globally titanium powder constitutes about five percent of the titanium metal market (Roskill, 2019). When considering titanium grades, CP titanium powder has the biggest Global Production Market Share at 59.46 % with titanium alloy powder trailing at 40.54 % (QY Research Group, 2017). Depending on the required properties, powders of both CP and titanium alloys are used within all major titanium industries.

A big portion of the interviewees indicated that South Africa should explore the production of spherical titanium metal powder. This could be pursued by importing CP or alloyed melted products, titanium scrap or high quality HDH powder to produce spherical titanium metal powders for local consumption. This is an important observation as the local market for titanium metal powder is dominated by AM and this industry requires spherical powder. Interviewees also mentioned that another market for the spheroidisation of titanium powder is to recondition off-specification powders. Spheroidisation technology can be applied to make the powder round again and/or to remove an oxide layer that formed on the surface thus reconditioning the powder. This would initially be applied to powders either produced locally or powders that are recycled from AM processes.

The vision element for local titanium metal powder production (stage 7 of the value chain) states that South Africa should produce enough powder for local demand and be a global supplier of titanium metal powder within the next decade.

Interviewees stated that based on local as well as global trends, a growth within the local titanium powder market is expected. Data collected during this study indicated that the industries that will be responsible for the market growth are aerospace, medical, leisure and automotive. The automotive was added to the future market as it is expected to be established in South Africa within the next three years. The leisure and automotive industries are expected to be a less stringent market as the quality of parts produced does not need to be as high compared to the aerospace and medical markets. The leisure markets include the production of watches (cases, bands and clasps), jewellery, spectacle components and frames, cell phone hinges and knuckles, sporting equipment, decorative hardware for luggage and purses as well as cosmetic cases. The market for the leisure industry is also referred to as the consumer market.

10.5.2. Product (How will South Africa get there?)

If South Africa succeeds with the direct production of titanium metal powder from $TiCl_4$, the product that will be produced will be an angular CP grade powder. As mentioned, this powder could then be spheroidised, used in MIM or consolidated to produce mill products. One of the main uncertainties of the production of titanium metal powder through the CSIR-Ti process is that the process is still being developed and therefore the application of the powder is still unknown. Feedback from interviewees stated that in order to establish what product can be produced from the powder, the powder itself would first need to be classified and quantified.

Products produced from spheroidal powders would depend on the morphology and grade of the powder. In the scenario where South Africa imports titanium for the purpose of spheroidisation the quality can be pre-determined depending on the client/market requirements. These powders can then be used to produce parts for the aerospace industry or less stringent industries.

10.5.3. Technology (How will South Africa get there?)

Based on the vision element obtained for this stage of the titanium metal value chain, within the next 10 years South Africa should be able to produce its own titanium metal powder with the $TiCl_4$ feedstock also being locally produced. For South Africa to achieve this 10 year vision element, a technology would need to be developed locally or sourced externally. Interviewees indicated three possible technology options for local technology advancements and two options for importing technologies from abroad.

Imported technology options:

- Option A: Import spheroidisation or atomisation technology and apply it to imported feedstock (e.g. sponge or melted products (electrodes)) or locally

produced feedstock (powders produced from the CSIR process or the HDH powders). Interviewees indicated that this option is the most likely to be implemented within the next decade.
- Option B: Collaboration with a company that already has access to an existing powder production technology and establish this technology in South Africa.

Local technology options:
- Option A: Successful commercialisation of the CSIR-Ti process. Overall, this option was identified as the second most likely option).
- Option B: The development of a novel powder production process (excludes the CSIR-Ti process).
- Option C: Commercialisation of the HDH method applied to imported sponge or melted products (electrodes) to produce angular powder.

10.5.4. Research and Development (How will South Africa get there?)

According to interviewees the local research on the direct electrothermal production of titanium metal powder should be continued. The leading process being researched is the CSIR-Ti process. A techno-economic analysis on this process has been conducted but the result is unpublished. This analysis could be updated based on the latest R&D progress and the global market for angular titanium metal powder. Interviewees indicated a need for this research to be supported by government and highlighted that this research should also be driven by an industrial partner. In parallel, research on the processing of angular titanium metal powder should be accelerated as this is the expected product from the process.

A techno-economic analysis is needed on the spheroidisation of titanium metal powder and/or related technologies. The outcomes of this study should determine the capacity of the spheroidisation machine required, the grade of the titanium to be produced (depending on the market), the spheroidisation technology required and the type of feedstock to be spheroidised. The techno-economics related to importing of this technology should also consider the import of HDH titanium powder to be spheroidised with this technology.

The production of titanium metal is a crucial step in the titanium metal value chain. From the results obtained in this research the direct production of titanium metal powder (stage 7 of the titanium metal value chain) is preferred above the conventional sponge route. It is therefore important that South Africa continues research in this stage. This research should however not be limited to the existing research, but alternative and new process routes should also be explored.

10.5.5. Resources (How will South Africa get there?)

Resources to be considered within this section are raw materials (or feedstock) and human capital. In the CSIR-Ti process titanium metal is produced in a molten salt medium. The composition of the salt is confidential, but the feedstock is $TiCl_4$ that is imported. Based on the overall vision for the local titanium metal value chain the $TiCl_4$ feedstock should be locally available within the next decade. Other feedstock for powder production includes titanium melted products, scrap, sponge or sponge fines as well as rutile or TiO_2. The bulk of these would have to be imported or recycled, but if South Africa were to use the FFC process (or a similar process) titanium powder could be produced from rutile.

It is still expected that South Africa will need to import high-grade spherical titanium metal powder suitable for the aerospace industry for the next decade. The aerospace industry has very strict rules and regulations and not only does the metal purity need to be approved, but the process as well. South Africa is training researchers in the production of titanium metal powder as well as spheroidisation.

10.6. Discussion: Roadmap for Titanium Powder Production

South Africa does not produce titanium metal powder on a commercial scale, but this stage of the titanium metal value chain has been identified as the second and final stage that should be added to the local value chain within the next decade (in addition to $TiCl_4$). In recent years this stage of the titanium metal value chain has made its mark within the global titanium metal industry. There are two main methods to produce titanium metal powder. The first is to follow the conventional sponge production route and add on to this by either obtaining sponge fines or generating powder from sponge, melted products, mill products and titanium scrap. The second method is by the direct production of titanium metal powder from $TiCl_4$ or high purity titanium concentrates (rutile and/or ilmenite slag).

The vision element obtained for this stage of the titanium metal value chain indicates that South Africa should localise the production of titanium powder within the next decade. This vision element, together with the vision elements for each stage of the local titanium metal value chain, was obtained from interviewing industry and R&D experts. The interviews were followed by a survey to confirm the vision elements. In addition, interviewees contributed to the construction of an overall picture on where each stage of the local titanium metal value chain is now and how the country would get to the determined vision element (where the country wants to go for each stage). Information was collected based on a generic technology roadmap layout and a summary of the results on titanium powder production are displayed in Table 32.

Table 32. Summary of titanium powder production (stage 7).

Where is SA now?	Market	• 100 % of the titanium metal powders used locally are being imported • Market dominated by the medical, aerospace and leisure industries
	Product	• South Africa does not produce angular or spherical titanium metal powder
	Technology	• South Africa does not have the required technology to produce angular of spherical titanium powder

	R&D	• Angular powder production
		  ○ The CSIR-Ti process is R&D focusing on the production of angular powder through metallothermic reduction of $TiCl_4$. Pilot scale testing is still ongoing
		  ○ Historic research on HDH powder production on imported titanium sponge
		• Spherical powder production
		  ○ Imported sponge fines have been successfully spheroidised
		  ○ Powders produced by the CSIR-Ti process have been successfully spheroidised
		• Research should be conducted on alternative and new process routes for titanium metal powder production (continuous)

	Resources	• Raw materials such as rutile and upgrade ilmenite slag are available as feedstock for the direct titanium metal powder production instead of using $TiCl_4$ • HCD are being built through the ongoing R&D on titanium metal powder production and spheroidisation • South Africa has access to relatively cheap electricity compared to developed countries • South Arica is committed to incorporate renewable energy into its local energy grid
Where does SA want to go?	Vision element	*The vision element for local titanium metal powder production is to have access to powder production technology by 2030 and to be able to satisfy the local titanium metal powder demand with additional powder export capability*
How will SA get there?	Market	• Local metal powder production to replace imported powder within the next decade • The local market for powder is expected to grow, driven by the aerospace, medical, leisure and automotive industries • South Africa should export titanium metal powders within the next decade

	Product	• Spheroidised powder
		  ○ The results indicated that the production of spherical titanium metal powder is like to be the first choice for local titanium metal powder production
		  ○ CP or alloyed powder
		• Angular powder

		○ The results indicated that the production of angular powder (thought) the CSIR-Ti process is likely to be the second choice for local titanium metal powder production. ○ CP grade powder
	Technology	• Imported technologies ○ Option A: Spheroidisation or atomisation technologies. *The results indicated that this is the most likely technology that will be used for local titanium metal production within the next decade.* ○ Option B: Existing direct powder production technology (international partnership) • Locally developed technology ○ Option A: CSIR-Ti process *The results indicated that this is the second most likely technology that will be used for local titanium metal production within the next decade.* ○ Option B: A novel powder production process ○ Option C: HDH on imported sponge
	R&D	• Angular powder R&D: ○ Continuation of R&D on the CSIR-Ti process ▪ A techno-economic analysis has already been done for this process (could be updated) ▪ This process is dependent on the successful production of titanium metal powder • Spherical powder R&D: ○ Spheroidised powders produced during CSIR-Ti research ▪ Techno-economic analysis on the spheroidisation of locally produced titanium metal powder ○ Conduct research on the spheroidisation of imported sponge fines, HDH powders, melted products and titanium scrap ▪ Techno-economic analysis on the spheroidisation of imported sponge fines, HDH powders, melted products and titanium scrap ○ Market study on the global need for spherical powder • R&D to explore alternative and new process routes for titanium powder production
	Resources	• It is expected that by the time a local powder production plant is commissioned the feedstock ($TiCl_4$) should be produced locally • Raw materials such as rutile and upgrade ilmenite slag are available as feedstock for the direct titanium metal powder production instead of using $TiCl_4$ • HCD are being built through the ongoing R&D on titanium metal powder production and spheroidisation • South Africa has access to relatively cheap electricity compared to developed countries • South Arica is committed to incorporate renewable energy into its local energy grid

The aim of collecting the information displayed in Table 32 was to construct an industry technology roadmap for this stage of the titanium metal value chain (stage 7). This roadmap indicates a 10 year plan on how South Africa can get to the determined vision element from its current position. For this stage of the value chain it means that the country needs to replace the import of titanium metal powder by the local production of titanium powder. Although South Africa is actively researching the production of titanium metal powder this process is complicated and progress is slow. If a local technology cannot be commercialised within the next decade it should be considered to import the required technology. The local roadmap for titanium metal powder production is displayed in Figure 42.

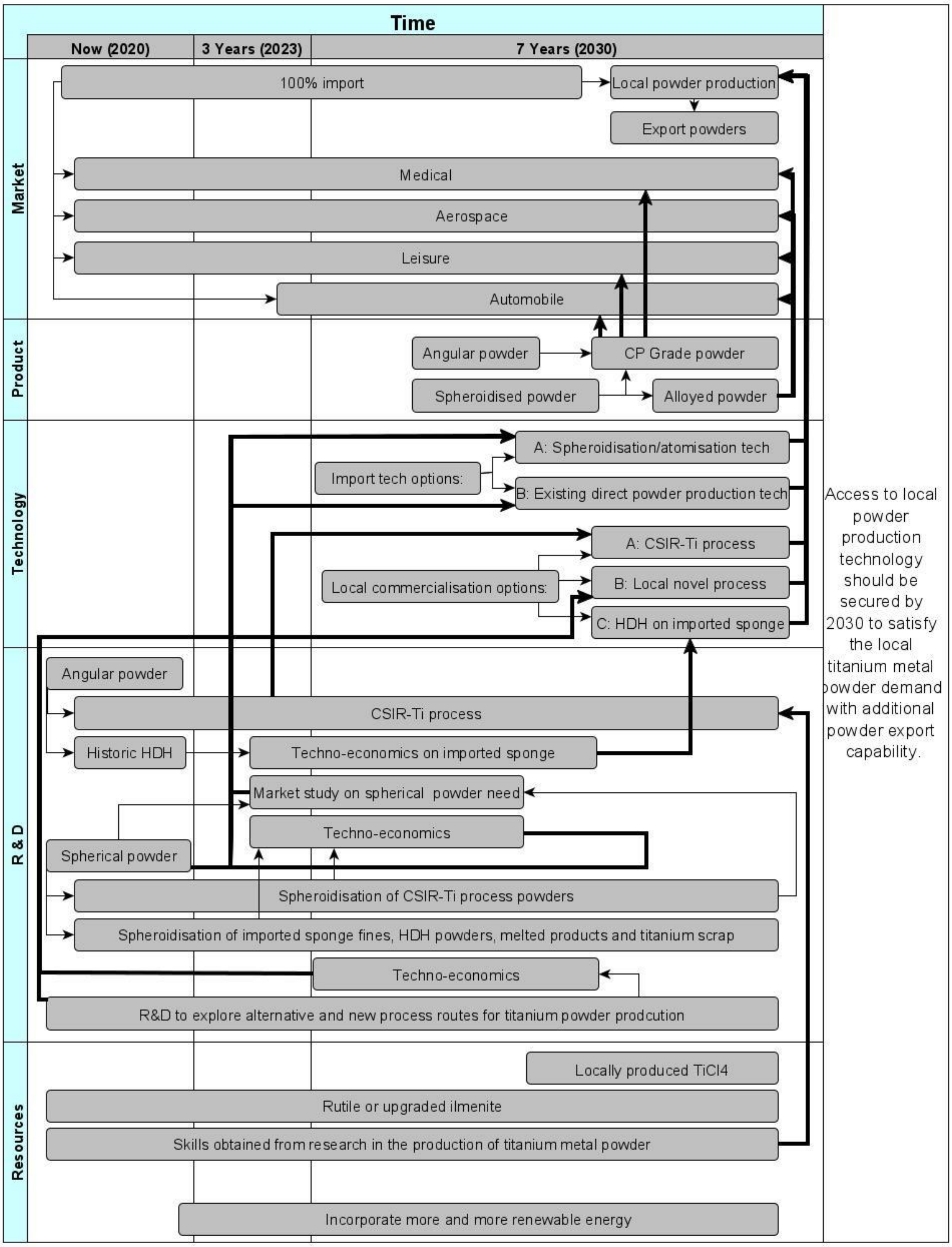


Figure 42. The local 10 year roadmap for titanium metal powder production (stage 7).

South Africa imports all the titanium metal powder used for the production of titanium metal powder products (stage 8 of the titanium metal value chain). Commercially the bulk of the imported powder is consumed to produce parts for the medical, aerospace and leisure industries. As the industry matures it is expected that the market will grow to include the automotive industry. According to the vision element for this stage of the value chain (stage 7), South Africa should produce its own titanium metal powder within the next decade and can then be able to supply its own local powder market. It is also anticipated that South Africa will be able to export locally produced powders within the next decade.

As all the locally consumed powders are imported and local spheroidisation is only applied on R&D level, no titanium powders are being produced in South Africa. It is expected that South Africa will be producing angular (CP) and/or spherical powder (CP or alloy) within the next decade depending on the selected technological route. For South Africa to produce titanium metal powder locally the required technology needs to be obtained. In this study the technology has been divided into two main routes namely local technology and imported technology.

When considering local technology, the first option is the production of angular titanium metal powder through the CSIR-Ti process. The results obtained from interviews indicated that this option is the second most likely technology to establish at this stage of the titanium metal value chain in South Africa. The CSIR-Ti process is still under R&D, but interviewees indicated that this process has the potential to be commercialised within the next 10 years. The second local technology option to consider is the establishment of a novel powder production process. This option is highly unlikely but indicates that South Africa should remain innovative and explore additional processes to produce titanium metal powder. The third local technology would be the application of HDH technology on imported titanium sponge. The HDH process was not developed in South Africa, but local R&D indicated that this process could be successfully implemented locally.

The import of an existing technology has been identified as the second technology route. In Figure 42 the first option for imported technology is spheroidisation or atomisation technology. Although it is not expected that this technology will be established within the next three years, it was indicated that this technology should be the overall first option for local powder production if found feasible (see R&D section below). Spheroidisation technology (or atomisation technology) could be applied to imported sponge, imported melted products (in the form of electrodes), imported angular powders and even to locally produced angular powders. The second option under imported technologies would require South Africa to obtain access to an already existing direct powder production technology. These technologies are fairly new in industry and unavailable for purchase. The result is that South Africa would need to enter into a partnership with a company holding this technology. Options for direct powder production technologies are the Armstrong metallo-thermic process, the FFC Cambridge electrolytic process or the CSIRO-TiRO process.

South Africa has dedicated large amounts of time and money into R&D to produce titanium metal powder directly. The leading R&D project is the CSIR-Ti process. This process aims to produce an angular CP titanium powder and R&D for this technology is expected to continue for the next decade or until it can be commercialised. An alternative for South Africa to consider is to apply the HDH process. Historically research has successfully been conducted using this process.

South Africa has also invested in R&D for spheroidisation. Local powders produced by the CSIR-Ti process as well as imported sponge fines have been successfully spheroidised. This research was conducted on a small scale using imported technology. The need has been identified for South Africa to continue this research while not only focusing on the spheroidisation of powders from the CSIR-Ti process but also imported sponge fines, HDH powders, melted products and titanium scrap.

In this study spheroidisation technology (Option A for imported technology) has been identified as the most likely technology for South Africa to develop this stage of the titanium metal value chain. Before this technology can be implemented a techno-economic analysis on the process is required. South Africa needs to determine whether it would be economically feasible to establish this technology on a commercial scale. A need for a market study on spherical powder was also identified by interviewees that stated that an overall global outlook is needed to ensure that South Africa produces the correct product required by not only the local, but also the global market (if pursuing exports). The second mostly likely technology identified for local titanium metal powder production is Option A from the local commercialisation technology options, the CSIR-Ti process.

The main focus in the resource layer was on raw materials (or feedstock) and human capital. South Africa does not produce sponge or melted products that are the feedstock for titanium powder production (considering the conventional sponge route). The country does not currently produce $TiCl_4$ that is the feedstock for the direct production of titanium metal powder. According to the vision elements obtained from this study this will change within the next decade as South Africa is expected to produce $TiCl_4$ locally. $TiCl_4$ is the precursor for the CSIR-Ti process. South Africa also has access to rutile and/or upgraded ilmenite which can be used as feedstock in some direct powder production processes. Human capital has been developed for this stage of the titanium metal value chain though continued R&D for more than a decade (mainly on the CSIR-Ti process).

10.7. Chapter Summary

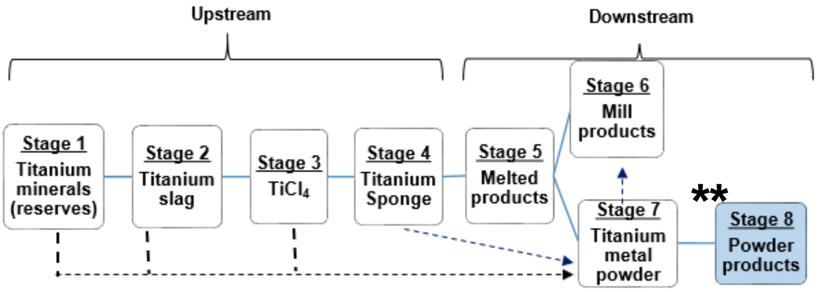
Chapter 10 covers the local and global position and outlook of the production of titanium metal powder. The chapter starts out by giving a background on what titanium metal powder is and the main methods used to produce it. The driver behind the titanium metal powder industry is the possibility of reducing the cost for titanium metal product production by eliminating process steps as well as saving time.

Titanium metal powder only makes up approximately 4 to 7 % of the total trade in titanium metal indicating that this is still a small market compared to sponge (± 57 %) and scrap (± 39 %). In contrast to the small quantities traded (compared to sponge) the cost for powder is much higher. Titanium metal powder is traded in a price range of US$ 99 – 261/kg compared to sponge US$ 2 – 10/kg.

South Africa is not producing titanium metal powder on a commercial scale, but the results obtained from this study indicate that the country should obtain this capability within the next 10 years. Two technological routes to achieve this was identified. The first route was the commercialisation of a local technology with the preferred process in this route being the CSIR-Ti process. The second route is to import an existing technology. The results indicated that the technology import route holds the most potential and more specifically importing spheroidisation technology. Spheroidisation technology is already available for purchase and could be applied to sponge fines, HDH powders, melted products (electrodes), scrap as well as locally produced powders from the CSIR-Ti process. Another benefit of this technology is that the size, shape and quality of the powder can be controlled to a large extent.

Significantly more R&D must be conducted before South Africa can select and implement a technology to produce titanium metal powder locally and the country needs to ensure that the correct approach is selected. To aid in this decision R&D should not only focus on the technology but also on the economics by conducting the required techno-economic analysis and market research. .

11. Chapter 11: Stage 8 (Powder Products)



***It is important to note that powder products refer to products made from titanium metal powder.*

11.1. Literature Review on Powder Processing Processes

The previous chapter elaborated on the powder production aspects of importance to titanium PM. Chapter 11 focuses on powder processing into products. Similar to Chapter 10, the three main parameters in PM (size, shape and quality) have an influence on the process used to process the powder.

The two most important parameters are shape and size. The shape determines the particle packing and a high metal density is preferred. The particle size distribution (PSD) is an important property as it determines the sinterability and surface quality of the final product. Finer powders sinter more readily and are therefore preferred. Froes, Gungor and Imam (2007) indicated that powders obtained from both the BE and the PA processes can be applied to NNS processes. These processes include powder pressing and AM, sintering, casting, cold spraying and semi-solid processing.

11.1.1. Additive Manufacturing (AM)

The definition of AM as defined by ASTM is "the process of joining materials to make objects from 3D modelled data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining (milling and forming)" (RAPDASA, 2016). This technology started in the mid-1980s as a rapid prototyping technology and evolved into a versatile new manufacturing technology (RAPDASA, 2016). Materials that can be used to generate AM parts include paper, metals, plastics, ceramics, glass and organic materials including living cells. These products are used in a variety of industries such as automotive, tooling, aerospace, medical implants and devices, jewellery and crafts as well as in the architectural industry (RAPDASA, 2016).

Additive Manufacturing is a new, emerging and disruptive manufacturing technology. The technology has been experiencing significant growth and has been identified as one of the key technologies for manufacturing in the future, specifically for South Africa (RAPDASA, 2016). Although there are several reasons for the growth in this technology the main reasons are a reduction in cost of manufacturing (using less material due to less waste formation), cultural development (a trend towards more custom products) and the fact that AM is a tool that allows designers to create unique products that are cheaper (Wohlers Associates, 2011).

AM technologies are applied in the manufacturing industry in rapid prototyping, rapid tooling, direct part production as well as on repair work on metals, plastics ceramics and composite materials (Liu *et al*., 2017). Technologies within AM that can be applied to metals are displayed in Table 33.

Table 33. AM technologies that can be applied to metals (Source: Liu *et al*., 2017).

AM Technology	Typical Market
Powder bed fusion (covers selective laser sintering, selective laser melting and electron beam melting)	Prototypes, tooling and final parts
Direct energy deposition (covers laser metal deposition (LMD), electron beam free forming fabrication)	Final parts and refurbishment and repair
Binder jetting	Prototypes, patterns for castings, creative industries; final parts (metals)
Sheet lamination	Prototypes, tooling, final parts (metals)

The metal specific AM technologies listed in Table 33 can be classified by the energy source (laser beam, electron beam and arc), the feedstock state (metal powder, wire and sheet) or the method of feed material (blown or powder bed). Other AM technologies are restricted to specific materials such as photopolymers (use a 3D printing method called vat polymerisation technology), polymers (use material jetting and material extrusion technologies) and waxes (use material jetting technology) (RAPDASA, 2016).

11.1.2. Powder Pressing and Sintering

Powder pressing and sintering is the general name given for processes that involve three basic steps namely powder blending, die compaction and sintering. Sintering is the thermal treatment of a powder at a temperature below the melting point of the main constituents in order to increase the strength of the metallurgical bonding of particles. Several processes can be used to achieve pressing and sintering (P&S) such as, metal injection moulding (MIM) and hot isotactic pressing (HIP). Powder pressing and sintering is the PM technique with the lowest cost (Bolzoni *et al*., 2012). The largest drawback of this process is that it results in a high residual porosity in the sintered parts that directly affects its mechanical properties (Bolzoni *et al.*, 2012).

11.1.2.1. Metal Injection Moulding

One of the most popular P&S techniques to produce near net shape products from titanium powder is by the process of metal MIM. The idea of MIM developed from plastic injection moulding and combines this technique with powder metallurgy (Froes, Gungor and Imam, 2007). The process of MIM has gradually been replacing more costly manufacturing processes for small-to-medium shaped precision components. This process is advantageous as it produces cheaper and more complex shaped parts while utilising almost all types of metals and intermetallic compounds. This process can be set up to produce large and small volumes of parts (Chang and Zhao, 2013). Figure 43 is a flow diagram for the MIM process.

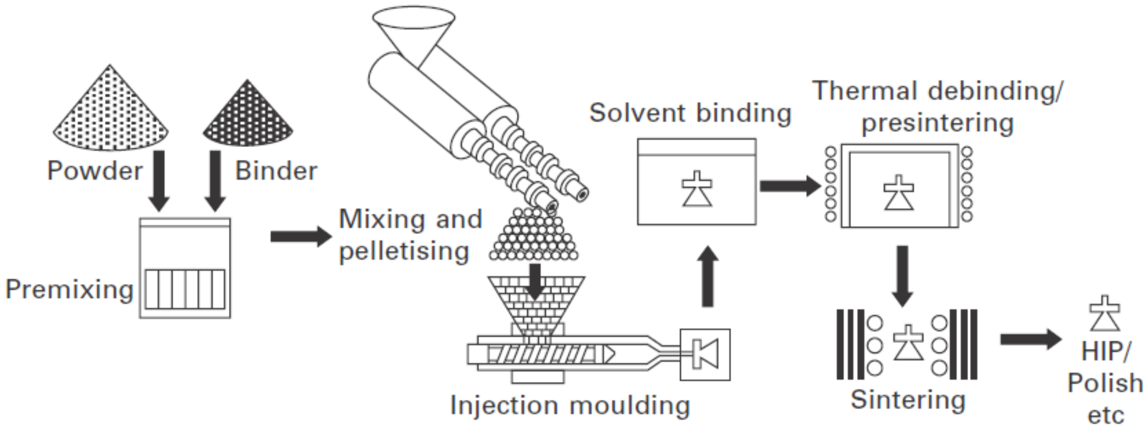


Figure 43. Flow diagram for the MIM process (Source: Chang and Zhao, 2013).

When applying the MIM process the cycle is started by preparing the feedstock. This is done by mixing fine metallic powder with a binder comprising waxes, polymers, lubricants and surfactants. The feedstock is then crushed and heated by an injection moulding machine before injecting it into the mould cavity under pressure (Chang and Zhao, 2013). After cooling, the solidified part is called a green part. The next step is to remove the binder components from the green part leaving behind a porous brown part. This brown part is then sintered resulting in a shrinkage of more than 95 % of the pore-free density (PFD) (Chang and Zhao, 2013). The shrinkage that occurs during sintering is one of the most important steps within MIM and should be controlled as it affects the final part's density and mechanical properties (Chang and Zhao, 2013).

Post-sintering the parts can be assembled, heat treated, densified (using HIP) and finished. This assists in improving some of the properties and HIP is one of the most important post sintering processes as it reduces residual porosity thereby improving the part's mechanical properties (Chang and Zhao, 2013).

Chang and Zhao (2013) provided the following list of properties that are important for selecting a powder to be used in MIM:

- particle shape (slightly non-spherical with an aspect ratio of 1.2:1.5),
- particle size (0.1-20 µm),
- mean particle size (10 µm recommended),
- tapped density (ratio of mass to volume occupied), the recommended is ≥50 % of the theoretical,
- angle of repose (above 45 °),
- compacted angle of repose (above 55 °),
- dense, discrete particle free of voids, and
- clean particle surface.

11.1.2.2. Hot Isostatic Pressing and Cold Isostatic Pressing

HIP is a process of fully consolidating parts at elevated temperatures through solid-state diffusion. The HIP process was already discussed in Chapter 9 (mill products) where the process is applied to treat conventionally casted titanium parts. HIP is also applied to PM parts as it forms part of the post-sintering steps used to consolidate titanium and titanium alloy powders with spherical powder particles (Chang and Zhao, 2013). The process for HIP on powder, as explained by Bolzoni *et al.*, (2012); and Chang and Zhao (2013) is firstly the encapsulation and degassing of powders while the containers are evacuated. Once this is done, heat (typically 800-960 °C which is below the alpha/beta transus) and isostatic (same from all directions) gas pressure (typically 100 MPa) is applied to the sealed container for two to four hours (Bolzoni *et al*., 2012). The result is densification of the component.

Cold isostatic pressing is performed at ambient temperature and pressures range from 207-414 MPa (max of 758 MPa). The high pressure is applied to a sealed container that is shaped for the application. The pressure medium used for CIP is water and oil where HIP is normally conducted under argon atmosphere (Neikov, Naboychenko and Yefimov, 2019).

The CHIP process is a combination of cold and hot isostatic pressing. In this process powders are first subjected to room temperature (cold) isostatic pressing and this occurs in a re-useable elastomeric container to obtain a preform with density higher than 85 % of theoretical density. Subsequently the preform is sintered at high temperature and isostatic pressure in a high pressure containment vessel to produce either a NNS part or a solid preform for future processing (Capus, 2016).

11.1.3. Alternative Powder Processing Techniques

Titanium metal powder casting is classified as a low-cost titanium manufacturing technique. The input material is required to be a low-cost material (such as sponge fines or powder from sponge). Casting techniques that can be applied are PAM and EBM as they offer the potential to make a NNS product from a single melt (Froes, Gungor and Imam, 2007). Other powder processing techniques are cold spraying, thermomechanical powder metallurgy (includes direct powder rolling, extrusion and powder compact forging), semi-solid processing, Field Assisted Sintering Technology Forging (FAST) and post-sinter forging (Zhang *et al.*, 2009).

11.2. Global Outlook: Titanium Powder Product Production:

Globally the market for AM is expected to grow. In 2018 the AM market was reported at US$ 8.44 billion and a 17.7 % growth is expected until 2027 (Smith, 2018). Similar growth is expected for the titanium AM industry. A 2018 Wohlers market report, state that a large portion of the growth will be attributed to the decline in the price of AM machines as the competition in the industry will increase. The reduced production cost will open additional markets to the AM industry with specific reference to personalised components (Cambell, 2018).

The main concept behind the production and utilisation of titanium powders is to produce a cheaper finished product faster with less waste material. Globally the market for titanium powder has developed in two main sectors. The first being driven by high value net-shape or NNS components mainly for the medical and consumer sectors. Parts produced for this section are mainly produced using costly production technologies such as MIM, AM and HIP. The second sector utilises the lower value angular powders that are used to produce high volumes of mill products (Roberts, 2018). The technologies utilised for the second sector are Direct Powder Rolling (DPR), CIP, HIP and vacuum sintering.

The main markets that utilise titanium metal powder are the aerospace, automotive and petrochemical/chemical industries. These industries would apply the required technology to a specific titanium powder (quality, shape and size) to produce the required product. Figure 44 indicates the industries that consume titanium powder.

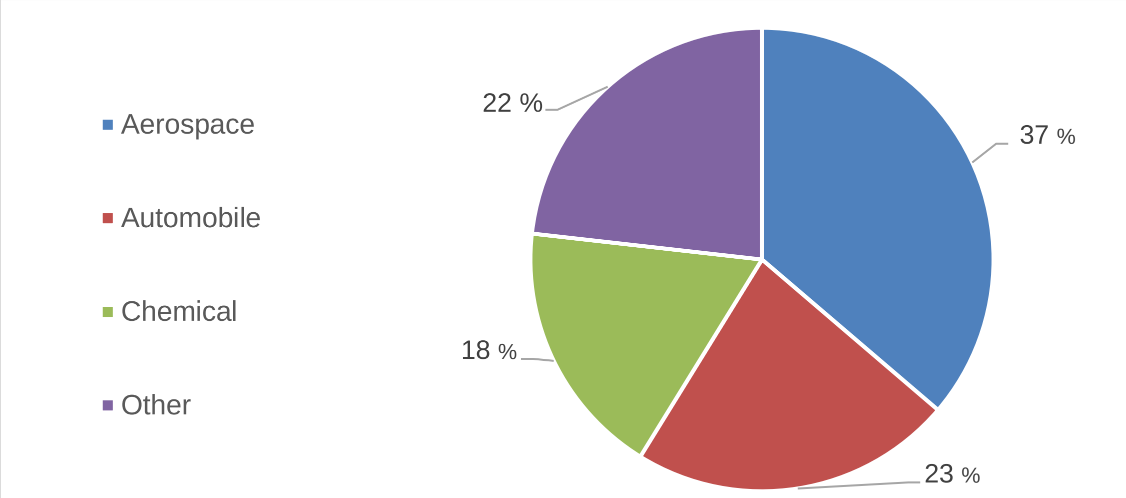


Figure 44. Titanium powder consumption market share by application in 2016 (Source: QY Research Group, 2017).

The cost of titanium powder products/components vary based on the cost of the powder used and the technology applied. As mentioned above angular powders are the cheaper option and according to Ivasishin (2006) the cost for part manufacturing using a conventional PM approach (such as CHIP) will cost 5-10 times more than the cost of titanium sponge.

MIM and AM require spherical powders and mostly powders of uniform size. This classification of powders into smaller sizes again adds to the cost and the result being a powder cost of US$ 40/kg to US$ 220/kg (German, 2010). According to the interviewees up to 100 % profit can be made from parts printed using AM technology.

11.3. Where is South Africa now?

Locally a few organisations are producing products from titanium metal powder with the three best-known being CUT (CRPM), Stellenbosch University and the CSIR's NLC (Aeroswift). CRPM has ten AM machines on site and is one the best equipped AM centres in the southern hemisphere. The centre specialises in developing medical devices (Cambell, 2018). The Aeroswift project is located at the NLC (RAPDASA, 2016). The 3D printing machine is a metal-additive system that produces parts from titanium powder by utilising a laser to melt the metal. This high speed additive manufacturing machine has a build volume of 2 m x 0.6 m x 0.6 m and is able to produce very large complex parts for the aerospace and other industries (IPAP, 2017). Figure 45 shows the Aeroswift machine as well as examples of titanium parts printed with it.

Figure 45. The Aeroswift machine (3D printer) on the left with examples of the parts produced on the right (Source: Vermeulen, 2018).

Locally the production off parts from titanium powder (stage 8 of the titanium metal value chain) is growing at a steady rate. A major part of this growth was driven by the idea of producing AM parts for the aerospace industry. Although some parts have been printed for the aerospace and leisure industry, this technology is still in an early stage of development and not commonplace in aerospace frameworks, even on a global scale. South Africa is actively researching this technology and its application in aerospace, but the major successes have been reached in the medical industry.

11.3.1. Market (Where is South Africa now)

The local market for titanium metal powder products is immature and small. There is a limited amount of private companies that produce titanium metal powder parts with the bulk of the country’s capability located at research institutions. Most of the commercial parts being produced are supplied to the local medical, aerospace and leisure industries. Interviewees indicated that based on the limited local market for titanium metal powder parts the customer base is not consistent, and the market can be classified as niche and specialised. This means that a customer can approach a powder product manufacturer with a specific request for a once of product and this could be produced at the agreed-upon fee.

11.3.2. Product (Where is South Africa now)

The bulk of the commercial products produced are generic medical implants for the medical industry (produced at CRPM). The centre specialises in developing medical devices such as implants and prostheses but is also active in the aerospace industry. Each generic medical implant is patient-specific meaning that each part is unique. The technology applied makes it possible for these parts (such as spinal cages) to be produced in volumes of hundreds (Cambell, 2018).

Parts produced for the aerospace industry include noncritical parts printed using the Aeroswift machine. These parts include throttle grips and brackets for the Advanced High Performance Reconnaissance Light Aircraft (AHRLAC). CRPM also reported on the production of parts for the aerospace industry, but did not report on its specific application.

The leisure industry (also referred to as the consumer market) is broad. Examples provided by interviewees of parts produced for this industry include cell phone covers, trophies, and several prototypes. Examples of prototypes are fishhooks, valve bodies, gun grips, heat exchangers and parts for solar powered eco-cars.

11.3.3. Technology (Where is South Africa now)

This stage of the value chain is still immature locally and therefore South Africa is mostly relying on international technology suppliers. South Africa has developed its own powder processing technology (the Aeroswift 3D printing machine), but other smaller laser fabrication or AM machines are imported. Locally produced titanium metal powder products are only produced using imported titanium metal. Interviewees stated that even if there was a local powder alternative, the bulk of the OEMs prefer imported powders that have already been qualified and approved by them for insurance purposes.

From the processes identified in the literature section for powder processing, AM is the biggest local consumer of titanium metal powder on commercial scale. This includes powder bed fusion as well as direct energy deposition. The bulk of the local machines (such as the Aeroswift machine) applies powder bed fusion technology.

11.3.4. Research and Development (Where is South Africa now)

South Africa is committed to powder processing research and therefore several institutions are actively conducting research in PM. MIM and HIP research on titanium is being conducted locally by the CSIR. A MIM facility has been established and offers a combination of tooling design and manufacturing capabilities for a wide range of small metal parts. Although one of the motivations for establishing this facility is to support the downstream titanium metal industry, other metal industries (e.g. aluminium) are currently benefitting from it. On industry scale this facility is already producing parts for the aluminium industry, but no commercial titanium parts have been produced (Science_Scope, 2018). Research on titanium is ongoing and a few titanium MIM success stories from this facility includes the production of anodised titanium bicycle brake callipers and deep-sea fishhooks composed of titanium. Science_Scope (2018) reported that a new industrial-scale MIM furnace is being acquired to scale-up the facility to mass production scale.

Research on laser metal deposition (LMD) is being conducted at Nelson Mandela University in Port Elizabeth. This research has developed thin cylindrical components while evaluating the amount of structural change and induced residual stresses on the parts. Ongoing research is focusing on fatigue testing of LMD components in atmospheric conditions and in saline solutions. Similar research is also conducted at the NLC.

Local research has also been conducted on powder consolidation (densification). This research conducted using powder pressing and sintering has successfully produced billets and bars (mill products) from titanium powders. According to the interviewees a lot of research is still required in this field as they were only able to achieve low-grades of products. The products produced were too porous and an improvement on density is required. The main reasons for the low density were attributed to the quality of imported powders. It is expected that higher quality powders will produce improved results, but these powders would be too expensive for the desired application of the product. DPR research is also being conducted at the CSIR but is in early phases of development.

Thermal spraying is the application of a coating onto an existing part to improve wear as well as corrosion resistance. Research on titanium thermal spraying (direct energy deposition) have been conducted at The South African Nuclear Energy Corporation (NECSA), but to date no record of the local commercial use of this technology has been obtained. According to the interviewees, titanium thermal spraying would only be applied to repair component surfaces or to create a rough surface to assist with joining in medical implants. Interviewees also stated that the equipment used to apply titanium thermal spraying differs from the conventional equipment used for other metals (molybdenum, copper, different stainless steels, ceramics and different carbides) as titanium reacts with the oxygen or nitrogen that is normally used. Titanium therefore needs a gas mixture of argon and helium for thermal spraying and this becomes a specialised operation.

11.3.5. Resources (Where is South Africa now)

No local commercially produced titanium metal powder is currently available and therefore both CP and alloyed powders are imported depending on the demand. According to interviewees the local production of titanium powder is not required for the production of titanium powder parts to be profitable, but it would be advantageous if a cheaper powder could be sourced locally. Although the feedstock is not yet available locally, the country is building up a large skillset within the PM field.

11.4. Vision Element: Where does South Africa want to go?

The vision element for the production of titanium metal powder products is to expand on the local capacity and expertise to produce high value products for both the local and export markets with the focus on medical, aerospace, leisure and automotive industries.

There was consensus among interviewees on the vision element to produce titanium powder products locally. One comment indicated that the timeline might be tight to become a world leader, but it is concluded that if a suitable niche product can be obtained this can be possible. This stage of the value chain is already developed locally, and South Africa should strive to be innovative to ensure global competitiveness.

11.5. How will South Africa get there?

Stage 8 of the local titanium metal value chain has been identified by interviewees as the most promising downstream stage of the titanium metal value chain. This stage of the value chain (especially AM) is growing at a high rate and could be a key contributor to the local economy if South Africa is able to utilise the opportunity.

100 % of the interviewees indicated that there will be a growth in PM within the next three years. This lines up with the global growth observed for this industry and especially AM. For the next 10 years, 95 % on the interviewees indicated a growth in the local PM field. The other 5 % indicated that they believe growth will be slowing down after the next three years due to market saturation and high costs of the products. According to the interviewees the growth for the PM stage will be attributed to (in no order of importance):

- a reduction in cost of the technology to produce PM parts (especially in AM),
- local expertise in the field of PM will grow,
- the export market will pull the local PM industry by expanding into new markets and this would stimulate further growth,
- government support promoting local market growth,
- local titanium awareness although PM would be a small portion of the whole market,
- larger imports of titanium metal powder to stimulate the market,
- the identification of new niche markets for PM parts,
- the local production of a cheaper titanium metal powder,

- local innovation within PM,
- an increased purchase of AM machines by the private sector motivated by government incentives,
- South Africa investing in producing parts for the automotive industry,
- the drive to replace mill product parts used in aerospace with PM parts, and
- the increased application of titanium in the medical industry.

11.5.1. Market (How will South Africa get there?)

According to interviewees the preferred global market for AM will remain the aerospace industry as it holds the most financial potential. For the local market interviewees indicated that the focus for the production of titanium metal powder products should be on the medical, the aerospace, the leisure and the automotive industries. The identified markets for South Africa differ from the global powder product market in that the global market includes the chemical sector more than the medical sector. The reason for this is that the South African medical market is already established with an export base that is profitable.

Interviewees also stated that the South African chemical industry is not as large compared to first world countries. Several different grades (CP and titanium alloys) of titanium are used within the chemical industry with the main required property being corrosion resistance. Titanium parts used within the chemical industry are mainly for chemical processing equipment, titanium containers, heat exchangers and titanium anodes. Titanium bars and sheets are also common. These parts are mainly produced through the conventional titanium metal production route (sponge route) and not from titanium metal powder. South Africa does not produce large amounts of cheap powder (e.g. HDH powder) to feed the chemical market and local production is leaning towards higher value industries such as medical, aerospace, automotive and leisure.

Interviewees indicated that over the next decade South Africa should increase its titanium metal powder product presence within the export market. The main issues identified for the PM market, were that South Africa is no longer a low-cost economy and that it should enter a niche high technology market to be able to compete with countries such as China.

Results obtained for this study indicated that the mill product market and the powder product market vary. The markets identified for mill products were the aerospace, medical and chemical industries and the markets for powder products were the aerospace medical, leisure and automotive industries. This variation is understandable as these two markets are not in direct competition with each other. Most of the interviewees agree that parts produced from PM (especially AM) will not replace large volume mill product production such as sheets and pipes. PM technology should be a resource that complements other technologies to produce products for applications previously deemed unfeasible.

11.5.2. Product (How will South Africa get there?)

Based on the market section above, the required products for the market would be driven by both local and global demand. Locally the titanium metal powder product market is dominated by the medical, aerospace and leisure industries and globally by the aerospace, automotive and chemical industries. It is expected that South Africa would include the automotive industry within the local titanium metal powder product market in the next decade, but not the chemical industry. The reasons for this were discussed in Section 11.5.1. The production of titanium metal powder products is still immature in South Africa, but is expected to expand within the next decade. Table 34 indicates titanium metal powder products that could be produced locally for each of the four identified industries within the local titanium metal powder product market.

Table 34. Product or parts that can be produced from titanium powder (Source: Roskill, 2019).

	Medical	Aerospace	Leisure	Automotive
Products	• Surgical tools, including scalpel holders • Implant devices, including chemotherapy pumps • Dental-implant anchors • Orthodontic brackets	• Jet-engine fasteners • Heat valves **Defence:** • Armour plating • Bulletproof vests and walls • Rifle and firearm components	• Watch cases, watch bands, watch clasps • Jewellery • Spectacle components and frames • Cell phone hinges, knuckles • Sporting equipment (e.g. golf clubs) • Decorative hardware for luggage and purses • Cosmetic cases	• Automotive gearshift knobs • Engine conrods

The 2019 Roskill report classified the products produced from titanium metal powder into three main categories. These categories help to identify what quality powder should be used (CP or alloy) and what processing technique to ensure the required properties. The first category is decorative items where the properties of titanium metal plays a smaller role than the market advantage (e.g. spectacle frames and watch bands). The second category relies on the mechanical and chemical (anti-corrosion) properties of the metal and makes it the preferred metal above stainless steel and other high-performance alloys (e.g. armour plating and surgical tools). In the third and final category the use of titanium metal is of utmost importance to ensure the product or part is adhering to stringent design specifications (aerospace and medical) (Roskill, 2019).

11.5.3. Technology (How will South Africa get there?)

South Africa is already making use of locally and internationally developed AM technology. For the country to remain relevant in the market it should ensure that it remains innovative and competitive with this fast-developing technology. Other PM technologies that should be commercialised for locally titanium metal powder product production within the next three years are MIM, HIP and within the next 10 years is titanium powder consolidation. These technologies should only be commercialised if economically feasible (to be discussed in R&D, Section 11.5.4).

11.5.4. Research and Development (How will South Africa get there?)

Titanium research has increased over the last two decades and according to a study done by Roux *et al.* (2019) spikes in this research are attributed to research done on PM. Titanium powder is complex as the shape, size and purity varies and research should continuously study alternative methods of processing this powder for different applications and industries. Interviewees indicated that the AM field is advancing rapidly in terms of technology and that South Africa (especially with the Aeroswift technology) should ensure that it remains innovative and competitive.

The research South Africa is doing in MIM, HIP and powder consolidation technologies should continue until these technologies are ready to be implemented. A need has been identified for techno-economic analysis to be conducted on the processes being researched to determine whether these technologies will be feasible when considering the local and global market. Alternative research to be conducted on titanium metal powder processing should include powder consolidation (direct powder rolling and semi-solid processing), cold spraying and semi-solid processing.

11.5.5. Resources (How will South Africa get there?)

The resource section will discuss two main aspects which are raw material (or feedstock to the stage under discussion) and HCD. The feedstock required for the production of titanium metal powder products is titanium metal powder in a specific shape, size and quality. The 10 year vision element for the previous stage of the value chain (titanium metal powder production) indicated that South Africa should be able to produce powder locally within the next decade. Interviewees however indicated that spherical high-grade titanium metal powder for critical parts within the aerospace industry would probably still be imported as there is a limited amount of titanium metal powder producers whose processes are accepted within the aerospace industry.

South Africa has had great success in developing AM technology. This development has contributed to human capital development within stage 8 of the titanium metal value chain (titanium powder products production).

11.6. Discussion: Roadmap for Titanium Metal Powder Products

South Africa is involved in this stage (stage 8) of the titanium metal value chain as the country is producing titanium metal powder products. The market for these products is immature and small with the bulk of the products produced also being used locally. There are several processes used to produce products from titanium metal powder, the ones most frequently discussed in this study are: AM, MIM, HIP, LMD, powder consolidation (press and sintering as well as DPR), thermal spraying (including cold spraying) and semi-solid processing. Out of these processes AM is the only technology applied locally on a limited commercial scale.

The vision element obtained for this stage of the titanium metal value chain (stage 8, titanium metal powder products) is to grow the local production capacity and expertise while specialising in niche part production for the medical, aerospace, leisure and automotive industries. This vision aspect has already been achieved in most of these industries (except for the automotive industry). The automotive industry is expected to be part of the market within the next three years. Information used to construct this vision element as well as the results presented in Chapter 11 was obtained through expert interactions. A summary of the information collected from these interviews (as well as the addition of secondary data) is displayed in Table 35.

Table 35. Summary of titanium metal powder products (stage 8).

Where is SA now?	Market	• South Africa has an immature, but small titanium powder product market with limited exports • The leading local market is for the medical industry, but the country also produces parts for the aerospace and leisure industries • An existing market for niche and specialised once-off products (including prototypes) that is not limited to a specific industry

	Product	• Medical industry:
		  o Medical devices such as implants, prostheses and surgical tools
		• Aerospace industry
		  o Non-critical parts such as throttle grips and brackets.
		• Leisure industry
		  o Broad field but includes cell phone covers and trophies
		• Prototypes
		  o Once-off fishhooks, valve bodies, gun grips, heat exchangers, solar powered car parts

	Technology	• AM technology is most popular technology both locally and globally. • The Aeroswift 3D printing machine (local powder processing technology) • Smaller laser fabrication machines (mainly imported)

	R&D	• South Africa is dedicated to research on titanium metal powder product production and four of the leading research areas are:
		  o MIM & HIP
		  o LMD
		  o Powder consolidation* using DPR and powder press and sintering
		  o Thermal spraying (including cold spraying)

	Resources	• Building local skillset with PM industry and R&D (AM, software design & MIM) • South Africa has access to relatively cheap electricity • South Arica is committed to incorporate renewable energy into its local energy grid
Where does SA want to go?	Vision element	*The local vision element for the production of titanium metal powder products is to expand on the local capacity and expertise to produce high value products for both the local and export markets with the focus on medical, aerospace, leisure and automotive industries*

How will SA get there?	Market	• The biggest market for titanium metal powder products produced in South Africa will be within the medical, aerospace, leisure and automotive industries • Growth within the local as well as the international/export market
	Product	• Medical industry: ○ Medical devices such as implants, prostheses and surgical tools • Aerospace industry ○ Continue with non-critical part production ○ Critical parts such as jet-engine fasteners and heat valves • Leisure industry ○ Watch casings, bands and clasps. ○ Jewellery ○ Spectacle components and frames ○ Sporting equipment ○ Decorative hardware for luggage and purses ○ Cosmetic cases • Automotive ○ Automotive gearshift knobs ○ Engine conrods • Prototypes
	Technology	• It is expected that the dominant technology and process for producing titanium metal powder products will remain AM • The Aeroswift 3D printing machine will produce powder products for the next decade • Imported laser fabrication machines will produce powder products for the next decade. • Additional technologies such as MIM, HIP and LMD for titanium metal are expected to be implemented within the next three years • Powder consolidation is expected commercialised within the next ten years
	R&D	• Continued R&D in PM to ensure South Africa remains up to date with global innovations (especially AM) • Continuous R&D on MIM, HIP and powder consolidation until commercialised • Techno-economic analysis on all technologies being researched • New research to include direct powder rolling, cold spraying and semi-solid processing
	Resources	• Local production of titanium metal powder within the next decade • Skills produced in PM though industry and R&D • Incorporate more and more renewable energy into the national energy mix

The information displayed in Table 35 was used to construct a roadmap for stage 8 of the titanium metal value chain (titanium metal powder products). This roadmap follows a 10 year timeline that is split into medium-term (three years) and long-term (seven years). As this stage of the titanium metal value chain is already established in South Africa, the production capacity as well as expertise within the field need to be improved. Out of the four suggested industries only the automotive industry is currently absent but is expected to be included within the next three years. The local roadmap for titanium metal powder production is displayed in Figure 46. The asterisk "*" in the figure indicates that powder consolidation has already been discussed in another roadmap Figure 39 (stage 6, mill product production) showing a jump between these two value chain stages.

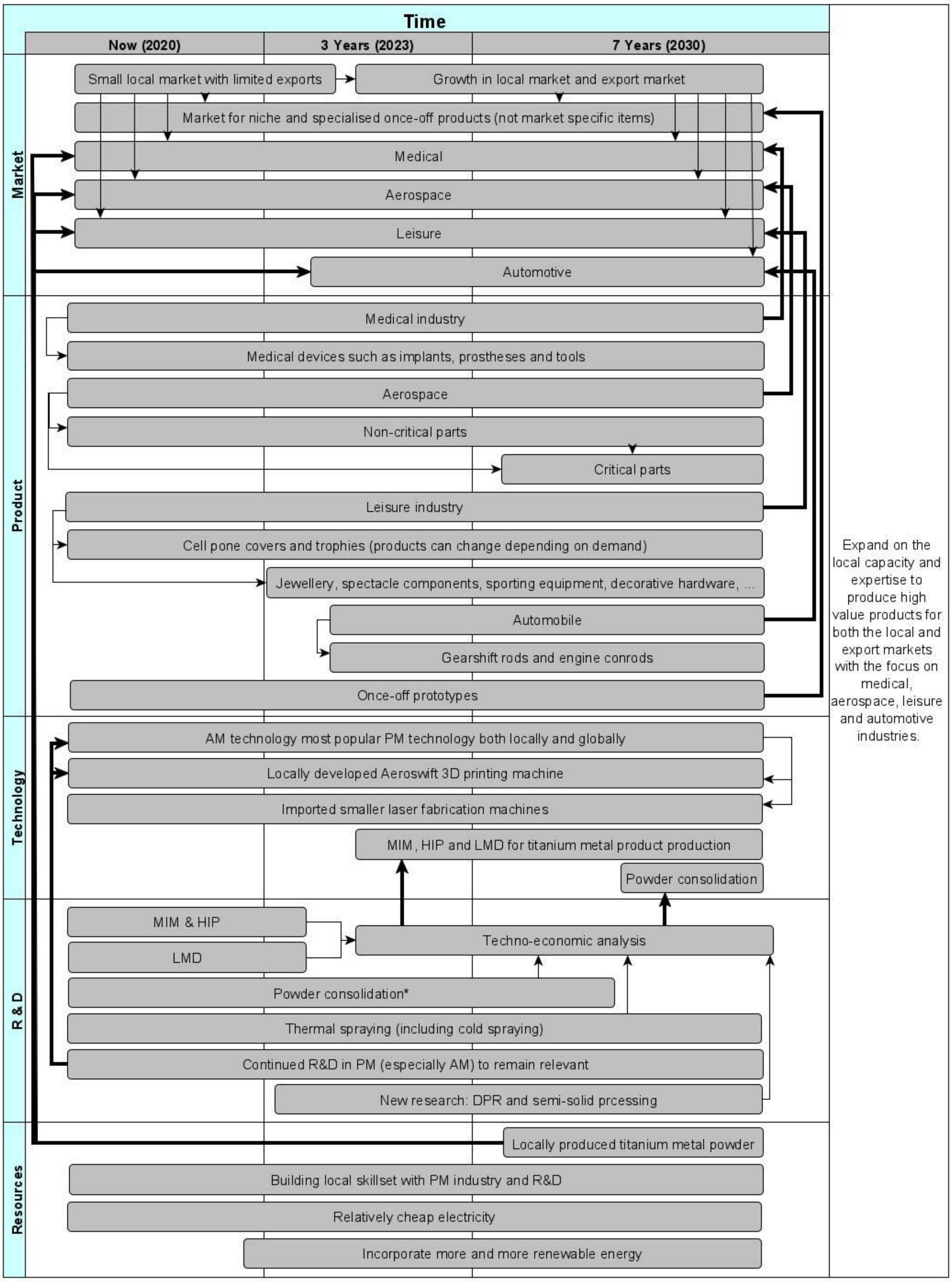


Figure 46. The local 10 year roadmap for titanium metal powder product production (stage 8).

The roadmap displayed in Figure 46 was constructed using the five layers of the generic technology roadmap layout as recommended in the methodology section. The thick arrows on the roadmap indicate the dependence and interrelations between layers and the thin arrows the relationship between themes (blocks on Figure 46) within the same layer. Each of the five layers are now discussed.

The local market for titanium metal powder product production is immature and small. The market is currently focused on producing parts for the medical, aerospace and leisure industries. The results presented in Chapter 11 indicated that there will always be a market for niche and specialised once-off products that is not confined to any industry. The expected future market for this stage of the titanium metal value chain includes the automotive industry as well.

Within the four identified markets, a systematic product evolution is expected for the local production of parts using PM. The medical industry is already established locally and producing advanced parts for generic medical implants, prostheses and medical tools. In the aerospace industry the focus should initially be on the production of non-critical parts such as throttle grips and brackets, but as expertise and confidence in AM technology's ability increases critical parts could be considered. Similar to mill product production the qualification and approval of use of critical parts may take time resulting in this not being possible within the 10 year roadmapping timeframe. Parts produced for the leisure industry are broadly used and the trend of printing leisure parts out of titanium is expected to continue for the next decade. The driver for this industry is the production of high value niche products such as jewellery and sporting equipment. Locally the automotive industry has only been explored on R&D level, but according to the results the application of PM for this industry should be developed locally in the next decade. Examples of products that can be produced for this industry are gearshift rods and engine conrods.

Locally and globally the most popular PM process is AM. This is currently the only commercial PM technology operating in South Africa, but according to the roadmap this is expected to change within the next three years with the incorporation of technologies such as MIM, HIP and LMD. In addition, it is expected that powder consolidation technology would also be available within the next decade.

One of the major success stories from the local drive to develop the titanium metal industry is the Aeroswift 3D printing machine. This high-speed AM machine can produce large and complex parts for the aerospace and other industries. The bulk of the remaining AM technologies used in South Africa have been imported. South Africa would need to stay innovative and advanced R&D should be applied to this stage to ensure that the country remains a prominent player in AM part production.

Except for AM, South Africa is also conducting research in other PM processes. A MIM research facility has been established at the CSIR and an industrial scale MIM facility is planned to be up and running within the next three years. This facility will require HIP technology to ensure that the parts produced are of the desired quality. Additional local research has also been conducted on LMD, powder consolidation and thermal spraying. Future R&D should include titanium direct powder rolling and semi-solid processing. Any new technology should be complemented with a techno-economic analysis of the process to ensure that it would be feasible and that the market would be able to consume the product. The PM field is evolving rapidly and to remain relevant South Africa needs to continuously conduct R&D within the field. The Aeroswift technology is a good example of local innovation, but interviewees indicated that this type of innovation must continue for South Africa to remain relevant in the PM field.

From the vision element for local titanium powder production (stage 7), South Africa is expected to produce its own titanium metal powder in the next decade. The availability of local powder is seen as a resource although producers of titanium metal powder products indicated that access to local powder is not required for stage 8 (powder part production) to be profitable. Interviewees did however indicate that local powder production might contribute to a powder cost reduction. As stage 8 (powder products) is an established stage of the titanium metal value chain, skills are being built not only through R&D, but also through industry experience. The last resource to consider is the relatively cheap electricity available in South Africa compared to developed countries. Although the country has been experiencing an energy supply crisis this should be resolved within the next decade with the implementation of the IRP. This plan ensures a more reliable and sustainable energy mix as it would include more and more renewable energy.

11.7. Chapter Summary

Chapter 11 is on stage 8 of the titanium metal value chain, titanium metal power products. This is the final stage of the value chain selected for the South African titanium metal industry. This stage of the titanium metal value chain is the most advanced stage as it represents the most value addition to the titanium minerals presented in stage 1 (Chapter 5). This is the fourth and final stage that is already established in South Africa.

The start of Chapter 11 discusses the available literature on powder processing followed by the global and local outlook for titanium powder products. The local outlook was determined through expert interactions combined with secondary data and the results presented in this chapter. These results were then used to produce a stage 8 specific industry technology roadmap to guide this stage until 2030. The roadmap considered five layers namely market, product, technology, R&D and resources.

This stage of the value chain is already established in South Africa and so is the market (although it is still immature). The existing markets for this stage are the medical, aerospace and leisure industries. The roadmap indicated that an additional market should be added to the list of industries namely the automotive industry. These markets differ for the global powder product markets as chemical is included for the global market. The local market is different to the global market as the country does not have a big chemical industry compared to first world countries. South Africa does also not have access to large amounts of cheap powder to produce the mill products (from powder) required in large scale by the chemical industry. South Africa is rather focusing on high value products from high quality (expensive) powders. The results also indicated that due to the nature of the technology, niche and specialised once-off titanium metal powder products (for no industry in particular) are also popular. It is expected that the local and export market for titanium powder products will grow within the next decade.

South Africa is already producing titanium metal powder products for the medical, aerospace and leisure industries. It is expected that products for the automotive industry should be produced within the next three years.

The most popular technology applied to this stage is AM. This is linked to the technology's ability to produce complex shapes for unique applications while producing much less titanium waste compared to mill products. The processing steps are also reduced and could potentially result in a cost saving. Locally South Africa has produced the Aeroswift 3D AM printing machine that is one of the world's biggest and fastest 3D printing machines. AM is only one subsection of PM and R&D in South Africa is also investigating other methods of producing parts from titanium powder. R&D processes that are expected to be commercialised in the near future are MIM, HIP, LMD and powder consolidation technologies (to produce mill products form powder). Future R&D identified for stage 8 include direct powder rolling and semi-solid processing.

The availability of resources could help this stage (stage 8) of the titanium metal value chain to function more effectively. The current resources that were identified were the human capital (skills) developed through the existing industry and R&D as well as the relatively cheap electricity within South Africa. The future resources are locally produced titanium metal powder (as per the vision element of stage 7) and the incorporation of renewable energy to the current energy mix to ensure a more reliant and sustainable energy supply.

12. Chapter 12- Titanium Scrap and Ferrotitanium

12.1. Introduction

Titanium scrap as well as ferrotitanium were excluded from the South African titanium metal value chain and therefore the roadmap produced for this industry. The reason for the exclusion is because no progressive advancements in terms of R&D or technology development are being observed in scrap processing and recycling or ferrotitanium production. Durr and Oosthuizen (2016) produced a management framework for titanium recycling in South Africa and concluded that basic processing of titanium scrap could be feasible but that any additional processing is currently not. Durr and Oosthuizen (2016) also stated that ferrotitanium production could be feasible in South Africa, but this should be specified to a greater extent before the ferrotitanium industry could be included in the South African titanium metal value chain.

12.2. Titanium Scrap

Titanium is a valuable material that results in its scrap trade also having a valuable market. Titanium scrap recycling can be referred to as a secondary sector (see Figure 47) and includes “new scrap”, “old scrap” and sponge scrap. New scrap is uncontaminated and of higher quality than old scrap. It is commonly generated as fabrication scrap that was left over from making products for industry or from mill scrap that was generated during melting, forging and rolling operations (Roskill reports, 2013). Old scrap is also referred to as obsolete scrap and represents final products that are retired at the end of their life cycle. Old scrap generally requires more processing as it contains larger quantities of contaminants and is therefore mostly used for ferrotitanium (Raj and Farrow, 1987; Roskill reports, 2013; Roskill, 2019). Ferrotitanium is used in the production of steel and other alloys. Any sponge that is off specification is considered as sponge scrap. This material is mainly the contaminated sidewall sponge that formed in the furnace in the Kroll reactor. This sponge is normally used in the steel industry as a titanium or ferrotitanium source (Roskill reports, 2013).

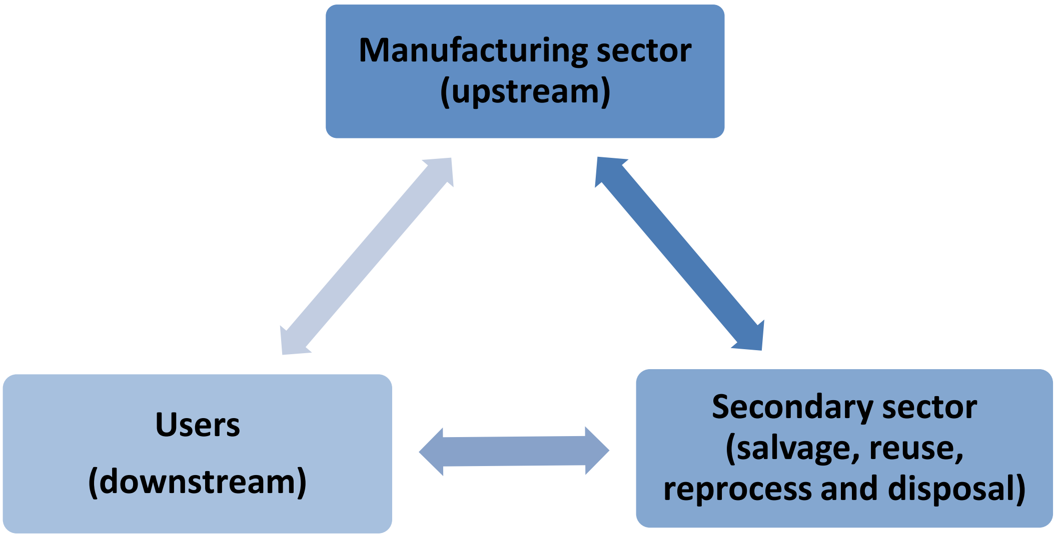


Figure 47. The titanium materials cycle (Adapted from: Raj and Farrow, 1987).

Handling and reprocessing titanium scrap has been researched by many researchers (Lu *et al*., 2012; Oh *et al*., 2014; Roskill reports, 2013; Zheng and Okabe, 2008; Durr and Oosthuizen, 2016) with the main aim of the research to develop more commercially viable scrap-recycling technologies. The main technologies applied to upgrade the quality of scrap is cold hearth technology and vacuum arc re-melting. Vacuum arc re-melting requires melting the scrap under a vacuum or an inert gas atmosphere. These conditions are applied to lower the risk of further oxygen contamination, which is the main and most common contaminant in titanium (Oh *et al.*, 2014). Cold hearth technology can be applied to contaminated scrap (old scrap) to remove contaminants and allow for the production of higher quality titanium metal (Roskill reports, 2013).

Neither of the two mentioned technologies reduce the oxygen concentrations within the titanium scrap, but research (such as the work done by Oh *et al.*, 2014) has indicated that a slight reduction of oxygen can be achieved through the HDH process or deoxidation in solid state (DOSS). The HDH process is used to produce titanium metal powder and should be considered as the third viable method to reprocess titanium scrap (after recycling and the production of ferrotitanium).

Although promising, these technologies add cost to the already expensive scrap material. When considering titanium alloy re-melting, the material that will be produced might have structural defects as well as the possibility to display an imbalance within the alloy composition (Oh *et al.*, 2014). These defects could affect the metal's unique properties. Roskill (2013) reported that VAR furnaces are not very efficient in melting scrap and that ISM, EB and PA furnaces are preferred.

To save cost, the titanium industry has adopted the near-net-shape manufacturing process. This process includes investment casting, superplastic forming and powder metallurgy (Roskill reports, 2013). Savings are applied by generating less scrap compared to when the final product is produced by machining. Roskill (2013) reported a reduction of scrap generation from 80 % to 40 % for most industries except for aerospace that still produces 80-85 % scrap from forging titanium parts. This industry also requires the use of “virgin” material meaning that titanium scrap does not re-enter the aerospace supply chain. Aerospace also generates titanium alloy scrap in comparison to industrial mill products that generally utilise a higher proportion of CP titanium scrap (Roskill, 2019).

12.3. Ferrotitanium

Ferrotitanium is an iron-titanium alloy. The titanium portion of the alloy is sourced either from recycled titanium scrap or from unwanted low-grades of titanium sponge and the iron portion from steel scrap. The industrial standard to produce ferrotitanium is by induction melting of titanium and steel scrap together. This produces a ferrotitanium with 70 % titanium. The traditional method for ferrotitanium production is to smelt titanium ores in an electric arc furnace together with aluminium or ferrosilicon to reduce the charge. This method is still in use and produces ferrotitanium with 25 % titanium and 40 % ferrotitanium (Roskill reports, 2013).

Ferrotitanium is used in the steelmaking industry as a cleansing agent as it is used for de-oxidation, de-nitrification and desulphurisation. The material’s cleansing ability is obtained from titanium’s high affinity for sulphur, carbon, oxygen and nitrogen. Titanium readily reacts with these elements removing them from the mix as a slag (Roskill reports, 2013).

12.4. Titanium Scrap and Ferrotitanium in South Africa

South Africa does not have the facilities to reprocess titanium scrap locally. In addition to the absence of facilities the local recycling industry has limited knowledge on the value of titanium alloys. The result is that it becomes the local titanium product producer’s responsibility to sell the scrap back to companies abroad at the low price of general non-magnetic of non-ferrous metals (Durr and Oosthuizen, 2016). This results in South Africa losing value from its imported titanium metal goods.

South Africa does not have a dedicated ferrotitanium production facility and therefore the country imports materials such as titanium, molybdenum and niobium for the production of stainless steel. Durr and Oosthuizen (2016) indicated that South Africa imported between 280 t and 600 t of ferrotitanium per year for the period 2000 to 2015 at an average cost of US$ 6 340/t. The exact use of the ferrotitanium is unknown, but according to Durr and Oosthuizen (2016) the imports are presumably for local stainless steel production.

More recent data indicate that a local stainless steel producer imports titanium scrap directly. The 2018 and 2019 imports for this one company was reported to be between 600 and 1 200 tpa. The price was classified as sensitive information, but it was indicated that the company paid approximately 71 % of the price for pure titanium. Using the price of ingots provided in Section 8.2 (US$ 15.5/kg or US$15 500/t) the cost of imported titanium scrap should be approximately US$ 11 000/t or according to the 2019 R/US$ exchange rate, ±R 145 820/t. When considering an average import of 900 tpa of titanium scrap (for the 2018 - 2019 production of stainless steel only), the market for titanium scrap was around R 131 million pa.

Based on the local market size for ferrotitanium production and the conclusion from the study done by Durr and Oosthuizen (2016), there is a possible feasibility to establish a ferrotitanium industry in South Africa. In contrast to this, personal communication with the stainless steel industry indicated that establishing a local ferrotitanium industry might not be as straight forward as assumed by Durr and Oosthuizen (2016). To produce stainless steel, titanium scrap with a high purity is required and specific quantities of aluminium and magnesium. This means that the confidence in the local ferrotitanium product will first need to be established. Durr and Oosthuizen (2016) also concluded that it is not feasible to establish a full scrap recycling industry locally, but that scrap processing could be feasible. This means that it will be too costly to set up all of the required processes locally (including sorting and purifying), but that a melting facility that processes scrap into melted products would make more economic sense especially if this could be incorporated in the local titanium metal value chain.

12.5. Chapter Summary

Based on the absence of scrap recycling and ferrotitanium production in the current South African titanium metal industry these two aspects were not considered for the roadmap produced for this industry. Chapter 12 on titanium scrap and ferrotitanium is still seen as an important aspect of the global titanium metal value chain and it was therefore decided to include this section in the thesis for completion and potential future opportunities.

Although South Africa is producing titanium scrap, there is no infrastructure or culture of recycling this metal locally. The result is that titanium scrap generated locally is exported at the same low cost as general non-magnetic of non-ferrous metals while titanium scrap for alloying (ferrotitanium) is imported at a higher cost. Titanium scrap is a valuable commodity and South Africa should investigate the production of HDH powder from the scrap or develop a screening process to produce high-grade scrap to the local stainless steel industry to use during alloy production.

13. Chapter 13- South African Titanium Metal Industry Roadmap

The path used to develop the roadmap was based on the generic technology roadmap structure as well as the key aspects identified from industry roadmaps. The methodology section (Section 4.4.2 see Figure 17) provided a layout guide to produce the overall South African titanium metal industry roadmap and indicated that four main phases should be used. These four phases are discussed in the remainder of this section.

13.1. Phase 1: Planning and Preparation

In order to produce a realistic and representative roadmap for the South African titanium metal industry, the global titanium metal industry was first evaluated. Through studying the global titanium metal industry, a titanium metal value chain was established that consists of eight stages, each stage dependent on a previous stage.

The planning and preparation phase followed the same sequence as indicated in the conceptual model designed for this study (Figure 13 and Figure 17). This model was based on the four keywords that were obtained from the research objectives and addressed by the research questions. The keywords were roadmap, value chain, fragmentation and vision.

The “roadmap” concept represented the input into the conceptual model. Firstly, a roadmap type was selected and a layout that determined the overall design of this study. The “value chain” concept was used to develop the titanium metal value chain construct used in this study. This value chain was developed by considering the global titanium metal industry and defining a value chain that could be applied to the development of a local titanium metal industry. Once this local value chain was established, “fragmentation” within this value chain, was investigated. From this investigation it was determined that only five countries globally have complete titanium metal value chains. These countries are China, Russia, Kazakhstan, Ukraine and the USA. Although the Ukraine is considered to have a complete titanium metal value chain, the country is not producing titanium metal powder, but it does produce titanium metal following the sponge route. This value chain is considered complete. South Africa was then classified as one of the several countries that has a fragmented titanium metal value chain as it only operates in four of the eight value chain stages. The aim of this study is to add value in understanding and suggesting a roadmap for the local titanium metal industry. This should be driven by an industry-wide vision. “Vision” indicates where the value chain should take the industry to. Vision *elements* for each stage of the titanium metal value chain were determined through expert interactions by conducting interviews and a survey. Secondary data also contributed to obtain a more complete understanding of the industry and its value chain. The roadmapping highlighted identified states of the industry over time (present, medium-term future, long-term future) The state of the industry was addressed in terms of the current ("Where South Africa is now?"), the vision ("Where South Africa wants to go?") and strategic interventions ("How South Africa will get there?"). Roadmapping was done for each stage of the value chain since it contains its own markets, products, technologies, R&D, and resources, these being the levels of the roadmap considered. The individual value chain stage roadmaps were then compiled into the overall roadmap for the South African titanium metal industry. The fragmentation of the South African titanium metal value chain is presented in Figure 48. The stages in blue are established locally (stages active in industry and R&D, see Table 10) and the stages under the grey arrow indicates where fragmentation is evident. The fragmented stages are being researched in South Africa (see Table 10).

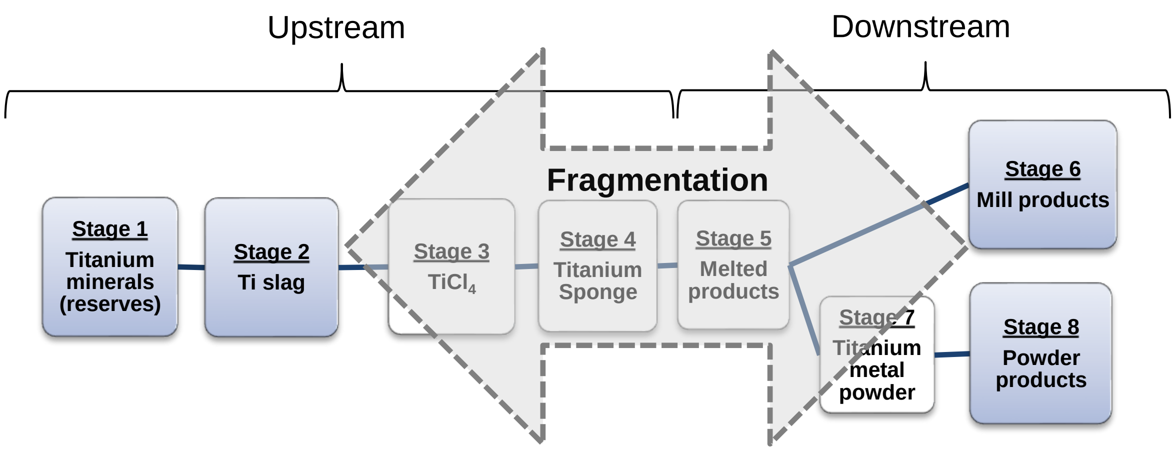


Figure 48. South Africa's current active titanium metal value chain stages and the fragmentation of the value chain (Adapted from: Roux *et al*., 2019).

Although South Africa has a fragmented titanium metal value chain, the country has the fourth most abundant titanium minerals reserves in the world. The abundance of titanium minerals combined with the value of titanium metal motivated the local government to investigate the expansion of the titanium metal value chain to support a better integrated titanium industry. The expansion of the value chain will benefit not only the titanium metal value chain, but also the titanium pigment industry which represents approximately 90 % of the titanium market. This drive has motivated research in every stage of the titanium metal value chain.

13.2. Phase 2: Visioning

Visioning is the key to any roadmap as it determines the future state of activity. Based on the fragmented nature of the local titanium metal value chain, vision *elements* were determined for each of the value chain stages. This was done by first interviewing 37 experts within the titanium field (research as well as industry).

The second step of the visioning process was a survey that was sent to selected experts within the stages of the titanium metal value chain. This confirmed the vision elements obtained from the interviews.

The vision elements for each stage of the titanium metal value chain are:

- **Stage 1 & 2: Titanium mineral (reserves) and titanium slag**
  These two stages are at high maturity, and the country should continue to mine and upgrade titanium mineral concentrates at a sustainable and efficient manner.
- **Stage 3: $TiCl_4$**
  Access to chlorination technology (through an industry partner) should be secured by 2030 and a large enough market must be acquired for pigment and metal production (local and Africa) for a local plant to be economically feasible.
- **Stage 4: Titanium sponge**
  South Africa does not foresee the need for a sponge production plant within the next 10 years.
- **Stage 5: Melted products**
  No local activity in melted products are foreseen in South Africa within the next 10 years and the development of a titanium melting facility is unlikely
- **Stage 6: Mill products**
  Expand on the existing local capacity and expertise to produce intermediate and final mill products for both the local and the export markets with the focus on medical, chemical and aerospace industries.
- **Stage 7: Titanium metal powder**
  Access to local powder production technology should be secured by 2030 to satisfy the local titanium metal powder demand with additional powder export capability.
- **Stage 8: Powder products**
  Expand on the local capacity and expertise to produce high value products for both the local and export markets with the focus on medical, aerospace, leisure and automotive industries.

These individual vision elements for the stages of the titanium value chain will now contribute to an overall vision for the titanium metal industry in South Africa for the next decade.

13.3. Phase 3: Titanium Metal Industry Roadmap Development

This phase consists of the development of the overall South African titanium metal industry vision. The overall vision development was done by a bottom-up process from the vision elements. Attention was also given to, prioritising needed markets, products, technologies, R&D and resources while considering timelines.

From the individual value chain stage vision elements an overall South African titanium roadmap vision was determined. This was done by grouping the vision elements with similar outcomes together to prioritise the needed markets, products, technologies, R&D, resources and timelines. Although each of the individual vision elements were validated the overall vision element is a suggestion produced from this study. The groupings of these value chain stages to produce an overall titanium metal industry vision for South Africa are now explained.

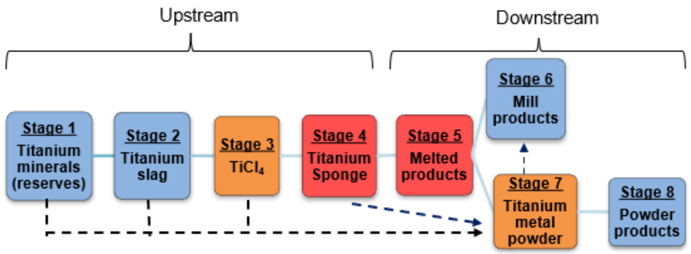
Stages 1 and 2 (titanium minerals and slag) are the two already established upstream stages of the titanium metal value chain. These two stages were grouped together throughout the result section as they mostly occur on the same site. The result is that the vision element for both stages indicate that these stages should continue in a sustainable and efficient manner. Stage 3 ($TiCl_4$ production) and stage 7 (titanium metal powder production) were grouped together as both should be added to the local titanium metal industry within the next decade. The results indicate that both these processes are only expected to be commercialised towards the end of the 10 year roadmapping period. Stage 4 (titanium sponge) and stage 5 (melted products) was grouped together as both should not be developed within the 10 year roadmapping timeline. These two stages will therefore be excluded from the final vision statement. Stage 6 (mill products) and stage 8 (powder products) were grouped together as both are already established locally on the downstream side of the titanium metal value chain and the vision elements for both stages indicated that the local capacity and expertise should be expanded to serve both the local and the export markets. The markets for these two titanium metal product stages differ as mill products are expected to focus on the medical, chemical and aerospace industries and powder products on medical, aerospace, leisure and automotive industries.

The 10 year (2021-2030) vision for the South African titanium metal industry is:

South Africa should continue to mine and upgrade titanium mineral concentrates in a sustainable and efficient manner. The country should commit to the establishment of two additional stages within the titanium metal value chain which is $TiCl_4$ production and titanium metal powder production. Capacity and expertise within the two already developed downstream stages (mill product and powder product production) should be expanded for both the local and the export markets. Within the mill product market, the focus should be on producing products for the medical, chemical and aerospace industries while the powder product markets should focus on medical, aerospace, leisure and automotive industries.

13.4. Phase 4: Roadmap Finalisation (The Overall Roadmap)

This section presents the overall roadmap for the South African titanium metal industry. The overall roadmap was designed to cover a medium-term period (three years) and a long-term period (additional seven years). Activities presented on the roadmap were selected to support the overall South African titanium metal industry vision within the 10 year timeframe. The overall roadmap style was selected to use a temporal approach (see Figure 3). This roadmap will therefore visually display the most important steps needed to achieve the overall vision. This overall South African titanium metal industry roadmap is presented in Figure 49.



The vision for the South African titanium metal industry:

South Africa should continue to mine and upgrade titanium mineral concentrates in a sustainable and efficient manner. The country should commit to the establishment of two additional stages within the titanium metal value chain which is $TiCl_4$ production and titanium metal powder production. Capacity and expertise within the two already developed downstream stages (mill product and powder product production) should be expanded for both the local and the export markets. Within the mill product market, the focus should be on producing products for the medical, chemical and aerospace industries while the powder product markets should focus on medical, aerospace, leisure and automotive industries.

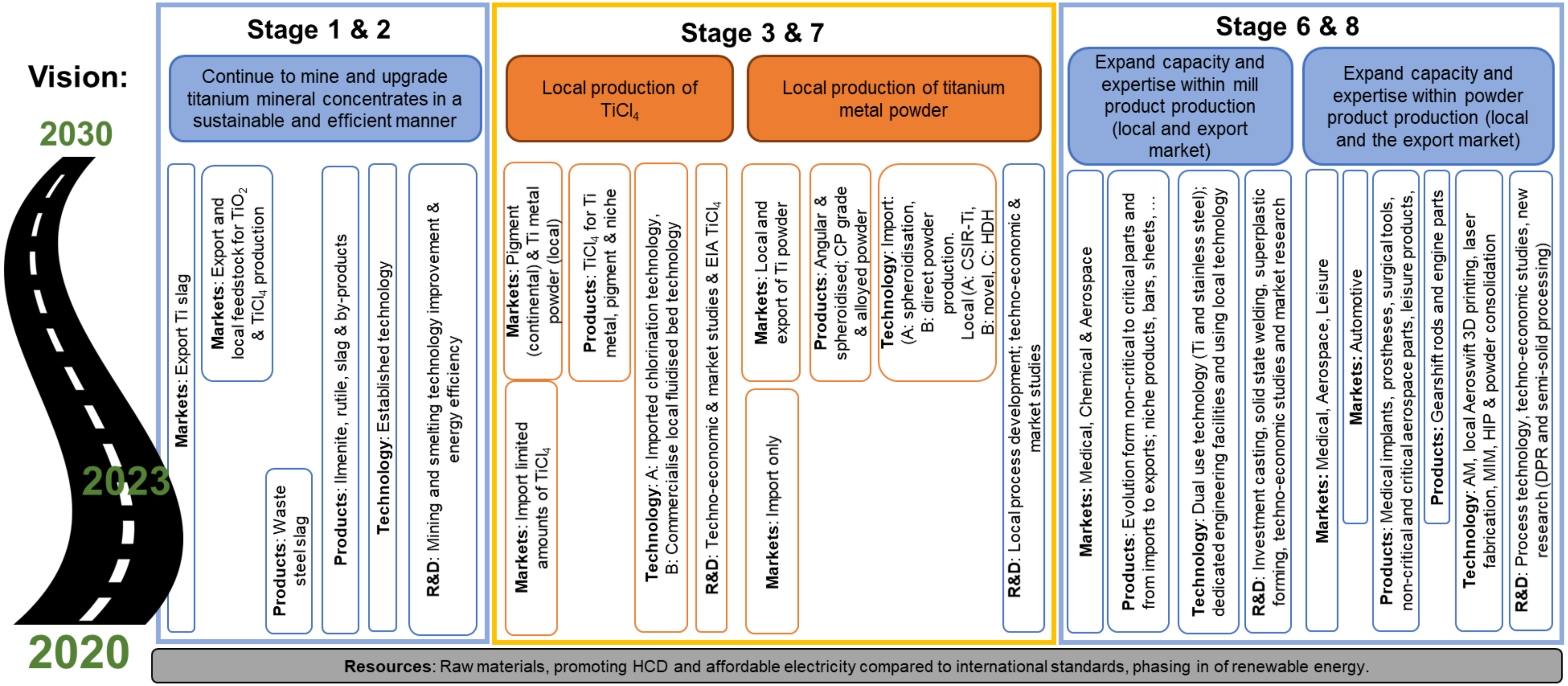


Figure 49. Graphic display of the overall South African titanium metal industry roadmap.

The roadmap displayed in Figure 49 applied the same three questions first presented in Section 2.1.2, Figure 2. These questions were: “Where is South Africa now?”, “Where does South Africa want to go?” and “How will South Africa get there?”. Therefore, the roadmap was constructed based on the overall vision for the South African titanium metal industry, “Where does South Africa want to go?”. The groupings identified for the value chain stages in Section 13.2 were used to indicate “How will South Africa get there?” from its current location, “Where is South Africa now?”. Individual elements discussed under the same roadmapping layer were grouped together in some cases and displayed on a combined time scale.

The sections indicated in blue are the already locally established stages of the value chain. The first two stages (stage 1 and 2) represent titanium mineral reserves (including mineral concentrate mining) and the upgrading of ilmenite into titanium slag. These two stages should continue local operations in a sustainable and efficient manner. The combined individual roadmap for these two stages is displayed in Figure 25. It is expected that the 100 % export of mined and upgraded titanium mineral concentrates would change to include the local market within the next 10 years. The titanium mineral concentrates are expected to be used as feedstock for TiO_2 (pigment) and $TiCl_4$ production. The technologies applied by the first two stages of the titanium metal value chain are established and R&D is focusing on improving these technologies to make them more energy efficient.

Stage 6 and 8 (mill product and powder product production) are also indicated in blue in Figure 49. These two stages are also established in South Africa. Locally the existing market for mill products (stage 6) are the medical, chemical and aerospace industries. The products produced for these industries are expected to expand as the local demand grows. The technologies applied by stage 6 are mainly divided into the dual use of other metal processing facilities (such as stainless steel facilities) and the production of mill products in dedicated titanium engineering facilities. The inclusion of local research technologies are expected to be added to the technological capacity within the next decade. Examples of technologies being researched are investment casting, solid state welding and superplastic forming. All of these technologies should first be subjected to techno-economic analysis and market studies before they start producing mill products for the titanium metal market. The individual roadmap for stage 6 (mill product production) is presented in Figure 39.

Stage 8 of the titanium metal value chain (titanium metal powder products) is also established in South Africa. Although immature the market for this stage is the medical, aerospace, leisure and automotive industries. The automotive industry is only expected to be added within the medium-term (next three years) of the roadmap. The products produced for these industries are expected to expand as this stage becomes more mature and the local production capacity increases. Technologies currently applied is AM dominated with the locally developed Aeroswift 3D printing machine one of South Africa's top innovations. R&D conducted in South Africa is not only focussing on AM but is also investigating other PM processing technologies (e.g. MIM and HIP). Future research suggested for this stage should include DPR and semi-solid processing. The individual roadmap for stage 8 (powder product production) is presented in Figure 46.

It was observed that the markets for mill products and powder products vary (stage 6 and 8). The markets for mill products locally are the medical, chemical and aerospace industries. Although the chemical industry is already a local market, no products are being produced for this industry locally and all parts are currently being imported. It is expected that local mill product production for the chemical industry will be available within the next three years. The titanium powder product market is currently focused on the medical, chemical and leisure industries and the automotive industry is expected to be added to this market within the next three years.

On the overall South African titanium metal industry roadmap, the section indicated in orange is the two value chain stages that are expected to be developed by 2030, these stages are the production of $TiCl_4$ and the production of titanium metal powder. The current market for $TiCl_4$ in South Africa is small and only limited amounts or the material is imported for R&D purposes. The results collected for this study indicates that a local market should be established within the next decade. The establishment of stage 3 ($TiCl_4$ production) is dependent on one of two technology options. The first would be the establishment of a titanium pigment plant as a $TiCl_4$ facility (based on existing technologies) would produce a significant amount of $TiCl_4$ that would be too much feedstock for only titanium metal production. The results indicated that even with a local pigment plant the amount of $TiCl_4$ produced would still be too much and therefore the need for additional markets to take up the surplus material was also identified. The second option would be the commercialisation of local fluidised bed chlorination technology. This technology is still being researched and still needs to undergo techno-economic analysis to determine whether it would be feasible to be commercialised. The preferred option for the establishment of $TiCl_4$ plant locally was therefore the construction of a $TiCl_4$ plant (imported technology) and the second option the commercialisation of local technology. The individual roadmap for stage 4 ($TiCl_4$ production) is presented in Figure 27.

The second stage that should be locally developed within the next decade is stage 7, the production of titanium metal powder. All of the powder used locally (by stage 8, titanium powder products) are being imported. The results obtained for this study indicate that this stage should be localised within the next decade. There are two main options for South Africa to achieve this within the next 10 years. The first and preferred option is for the country to invest in imported spheroidisation technology to produce spherical powders from imported sponge fines, HDH powders, melted products and titanium scrap. The feasibility of this option should first be confirmed through a techno-economic analysis as well as a market study to identify the need for local and global spherical powder. The second preferred option is the commercialisation of local technology, the CSIR-Ti process. This process is still in the R&D phase, but if developed within the roadmap timeline would produce an angular CP grade titanium metal powder. The individual roadmap for stage 7 (titanium metal powder production) is presented in Figure 42.

The main resources discussed for each of the value chain stages were raw materials (included feedstock for a specific stage), HCD as well as electricity. The resources are displayed at the bottom of Figure 49.

The value chain with the colours used in Figure 49 is displayed in the top right-hand corner of the roadmap. The two stages indicated in red, stage 4 and 5 (titanium sponge and melted product production) are not expected to be developed within the next decade and was excluded from the roadmap presented in Figure 49.

This roadmap has the same focus as the South African AM Strategy (RAPDASA, 2016) as both will drive the development of niche areas that will enable access to high priority opportunities. These opportunities can then be elaborated on to contribute towards South Africa's socio-economic imperatives. Advantages already existing in South Africa should be selected as drivers. These advantages include South Africa's natural resources, existing titanium markets and the established R&D capabilities. Focusing on these advantages will directly impact the country's economy.

14. Chapter 14: Conclusions and Recommendations

14.1. Overview

This chapter aims to provide a summary of the context and contribution of this research. One main and three sub-objectives were established for this research together with seven research questions. The main objective was to produce a roadmap for the titanium metal industry of South Africa and the sub-objectives were to establish a vision for the local titanium metal industry, to investigate the global titanium metal value chain and to determine South Africa's position in the fragmented global titanium metal value chain. All of the objectives were achieved by applying the conceptual model introduced in Chapter 3.

The research questions aim to address the objectives and a discussion on each research question will provide context to the work that was conducted. Results as well as the roadmap vision elements (for each stage of the titanium metal value chain) were obtained from primary sources (interviews and surveys with industry and R&D experts) as well as through secondary sources (book chapters, journal articles, market reports, news articles and company websites). The results contributed to answering the research questions.

This chapter is divided into four sections. The first section discusses the outcome of this research. The second section highlights the research objectives and research questions. The third section addresses the contribution to new knowledge on theory and practice and the final section makes suggestions on future research.

14.2. Outcome of the Research

The outcome of this research is a roadmap for the South African titanium metal industry. Since the publication of "The Beneficiation Strategy for the minerals industry of South Africa" in 2011 (DMR, 2011), the local drive to improve and expand on value addition within the titanium industry has been pursued. Although a structured R&D programme that focused on several key stages of the titanium metal value chain was followed on national level by R&D communities, no official titanium industry roadmap was published that displayed the vision for the industry or R&D. This research addressed the need identified by "The Beneficiation Strategy for the minerals industry of South Africa" to expand local value addition by recommending the addition of two value chain stages to the existing titanium metal value chain. These two stages are the local production of $TiCl_4$ and the local production of titanium metal powder.

The titanium industry is complicated by the fragmented nature of its value chain and this has an influence on the value chain development in South Africa. In order to address the fragmentation within the titanium metal value chain, 7-stage specific roadmaps were developed (stage 1 and 2 were combined). These seven roadmaps had their own vision element that was used to create the overall South African titanium metal industry vision. This industry vision can be used as the driver for the South African titanium metal industry roadmap.

14.2.1. Use of the Conceptual Model to Develop a Roadmap Structure

Roadmapping is a future oriented analysis tool that brings technological innovations, policies, as well as business and social drivers together. The roadmap type selected for this study was an industry technology roadmap as this roadmap type focuses on guiding the development, commercialisation and deployment of a new technology. This was identified as the key need for South Africa since four of the eight titanium metal value chain stages are not developed in the local industry.

To evaluate and "map" the current and future state of the South African titanium metal value chain, a conceptual model was generated to create a representation of the titanium metal industry. This was done by using keywords from the research objectives as concepts and ideas to build the conceptual model. The four keywords selected were roadmapping, value chain, fragmentation and vision.

As per the conceptual model, "roadmapping" (first keyword) was the start of the model. First roadmapping is applied through selecting the type and the design of the roadmapping model that was used throughout the study. The roadmap model applied a generic technology roadmap layout that elaborated on market, product, technology, R&D and resources, each representing a roadmap layer. The second keyword was "value chain". The roadmap model (the five layers) was applied to each stage of the identified titanium metal value chain to determine the current state ("Where is South Africa now?"), the vision ("Where does South Africa want to go?") and process ("How will South Africa get there?"). This allowed the study to determine the "fragmented" (the third keyword) nature of the local titanium metal industry value chain and the outcome was that it should remain fragmented for the next decade. The fourth keyword was "vision". This refers to the overall vision of the South African titanium metal industry and was determined by selectively combining all of the vision elements from the individual stages of the value chain. This vision was then used as a driver to develop the overall South African titanium metal industry roadmap.

14.2.1.1. Vision(s)

The vision used in roadmap construction is a consensus view of the future landscape available to decision makers. The vision outlines the desired future but not the path towards it.

The vision elements for the individual stages of the titanium metal value chain were obtained from industry and R&D experts. 37 interviews were conducted. Interviewees were purposively selected based on their involvement with the value chain stages. Although some of the titanium metal value chain stages are not applied in South Africa, interviewees with respectable knowledge (e.g. international participation on all of the value chain stages) contributed to the results. Interviewees were asked where they see the local titanium metal industry within the next three years as well as in the following seven years. The results obtained from the interviews were then consolidated and a survey distributed to 17 experts with specific domain knowledge selected from the interview pool. Sufficient participation was observed for each stage of the titanium metal value chain. The aim of the survey was to validate whether the vision elements were acceptable for each stage of the titanium metal value chain over the next decade.

The vision elements for each stage of the South African titanium metal value chain, as determined through the interaction with experts in the industry and R&D are stated below.

- **Stage 1 & 2: Titanium mineral (reserves) and titanium slag**
  These two stages are at high maturity, and the country should continue to mine and upgrade titanium mineral concentrates at a sustainable and efficient manner.
- **Stage 3: $TiCl_4$**
  Access to chlorination technology (through an industry partner) should be secured by 2030 and a large enough market must be acquired for pigment and metal production (local and Africa) for a local plant to be economically feasible.
- **Stage 4: Titanium sponge**
  South Africa does not foresee the need for a sponge production plant within the next 10 years.
- **Stage 5: Melted products**
  No local activity in melted products are foreseen in South Africa within the next 10 years and the development of a titanium melting facility is unlikely
- **Stage 6: Mill products**
  Expand on the existing local capacity and expertise to produce intermediate and final mill products for both the local and the export markets with the focus on medical, chemical and aerospace industries.
- **Stage 7: Titanium metal powder**
  Access to local powder production technology should be secured by 2030 to satisfy the local titanium metal powder demand with additional powder export capability.

- **Stage 8: Powder products**
  Expand on the local capacity and expertise to produce high value products for both the local and export markets with the focus on medical, aerospace, leisure and automotive industries.

In order to produce an overall 2030 vision for the South African titanium metal industry stages 1 and 2, 3 and 7 as well as 6 and 8 were grouped together and their vision elements combined:

> *South Africa should continue to mine and upgrade titanium mineral concentrates in a sustainable and efficient manner. The country should commit to the establishment of two additional stages within the titanium metal value chain which is $TiCl_4$ production and titanium metal powder production. Capacity and expertise within the two already developed downstream stages (mill product and powder product production) should be expanded for both the local and the export markets. Within the mill product market, the focus should be on producing products for the medical, chemical and aerospace industries while the powder product markets should focus on medical, aerospace, leisure and automotive industries.*

14.2.1.2. Value Chain

A value chain represents the activities or processes required to make or sell a specific product. The titanium metal product value chain used in this study consisted of eight product stages, each being dependent following a specific precursor. The eight stages selected for this study were obtained from literature and specifically from following the layout of the Roskill 2013 and 2019 market reports on titanium (Roskill reports, 2013; Roskill, 2019). The eight selected stages are displayed Figure 50.

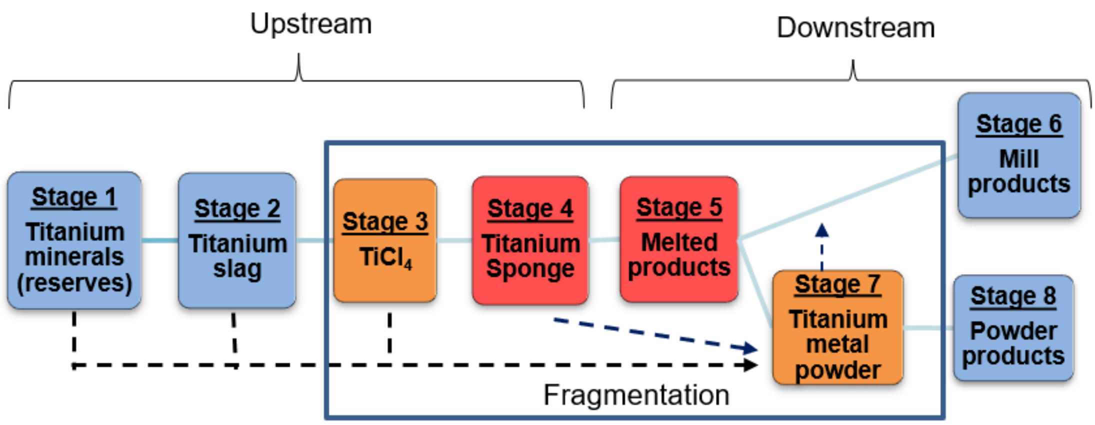


Figure 50. Fragmentation indicating the gaps in the South African titanium metal industry. The blocks in blue are established in South Africa. Blocks in orange should be developed in the next decade and the blocks in red should not be developed within the next decade (Adapted from : Roux et al., 2019).

The blocks in blue (Figure 50) represents the stages of the titanium metal value chain that are already established in South Africa. The blocks in orange represent the two additional stages of the metal value chain that should be developed within the next decade (determined through the visioning process. The blocks in red represent the two stages of the titanium metal value chain that should not be developed in the next decade.

14.2.1.3. Fragmentation

Production fragmentation occurs when either goods or services are produced in separate geographical locations (not in the same country). Countries exposed to fragmentation find it difficult to become more involved in the global value chain due to capital cost and product competitiveness. Fragmentation is not necessarily only negative as it promotes international trade and intermediate product exchange.

Globally the titanium metal value chain is mostly fragmented with only five countries having a complete titanium metal value chain. South Africa is one of many countries that has a fragmented value chain as only four of the eight value chain stages are established. Figure 50 indicates the local titanium metal value chain fragmentation.

One of the research questions aimed to establish whether South Africa should develop a complete titanium metal value chain or retain a fragmented one. This will be discussed in more detail in the next roadmapping section (Section 14.2.1.4), but the conclusion was that the South African titanium metal value chain should remain fragmented for the next decade. The results did however indicate that two additional value chain stages should be added to the current value chain structure by 2030, even though, the South African titanium metal value chain should remain fragmented. The stages to be added to the local value chain are $TiCl_4$ production (stage 3) and titanium metal powder production (stage 7).

14.2.1.4. Roadmapping

The roadmap developed for the South African titanium metal industry was designed to cover a medium-term period (three years) and a long-term period (10 years). The results therefore consider the current state of each stage of the local titanium metal value chain and according to the determined vision element, provides a three- and a 10 year roadmap on how to achieve these vision elements.

The analysis type that was selected for this research is based on a market-pull approach. The titanium industry is highly competitive with a few countries dominating the global trade (USA, China, Japan and Russia) of titanium products. For South Africa to be able to create a global presence within this market the country must be able to compete with these countries in the selected value chain stages. This competition would be for internal and external trade as the cost to import certain value chain stage products might be cheaper from other countries e.g. China compared to local production. In such a case the South African government would have to implement regulation in the form of additional import tax and export incentives (at least in the short-term) to give the local industry the opportunity to prepare to compete. The market-pull approach would therefore ensure that the country only develops stages of the titanium metal value chain that are able to compete on a global scale.

To date the South African government has developed the titanium metal industry using a technology-push approach. For the downstream industry side, a technology-push approach was taken for the development of the Aeroswift large scale 3D printing machine. This technology was designed before a clear market was defined and the technology was a first globally. Local R&D that is also being driven by technology-push approach, is the research on $TiCl_4$ production and titanium powder production. Locally there is not a big enough market for a $TiCl_4$ production facility, but there is a surplus of feedstock minerals. Therefore, a technology-push approach was followed whereby the aim was to produce a technology driven by the abundance of mineral feedstock (stage 1 of the titanium value chain) and not by market demand. R&D on powder production (CSIR-Ti process) also follows this approach as the R&D is focusing on producing a new technology for a non-prioritised and unquantified market.

The overall South African titanium metal industry roadmap presented in this study follows a market-pull approach, represented by the vision. The South African titanium metal value chain should remain fragmented and the two additional stages are expected to be added to the value chain ($TiCl_4$ production and titanium metal powder production) within the next decade. These two additional stages should only be pursued if they can provide a competitive advantage in the global titanium market.

The overall roadmap design was a combination between the generic technology roadmapping multi-layered layout, and an analysis grid created through studying six industry roadmaps. Based on the fragmented nature of the titanium metal industry each of the value chain stages were first roadmapped separately using a temporal roadmap classification. This allowed each roadmap to follow a time based layer, clearly indicating where that stage is now, where it wants to go (the vision) and how to get there. This roadmap followed a temporal roadmap approach and was visualised. This roadmap was a visual presentation of what is required for South Africa to achieve the overall South African titanium metal industry vision.

This roadmap has the same focus as the South African AM Strategy (RAPDASA, 2016) as it will drive the development of niche areas that will enable access to high priority opportunities. These opportunities can then be elaborated on to contribute towards South Africa's socio-economic imperatives. Advantages already existing in South Africa should be selected as drivers. These advantages include South Africa's natural resources, existing titanium markets and the established R&D capabilities. Focusing on these advantages will directly impact the country's economy.

14.3. Answering the Research Questions

The following section will elaborate on the research questions and discuss the answers obtained from the study. Each question will be stated followed by the answer.

1. **Which roadmap type should be applied to the South African titanium metal industry?**
   The roadmap type selected for the South African titanium metal industry was an industry technology roadmap. This roadmapping type was selected to enable the roadmapping process to focus on the development, commercialisation and deployment of new technologies that are recommended for the local titanium industry in the next 10 years. South Africa has an emerging economy and economic, social and environmental challenges must be considered when constructing a roadmap for the country. From the literature review section an industry technology roadmap should be able to solve the following three problems.

- *Problem 1 - The supply capability of scientific and technological resources.*
  This problem was solved by investigating the state and capabilities of local R&D. The two stages of the titanium metal value chain expected to be added to the local titanium metal industry value chain within the next decade are $TiCl_4$ production (stage 3) and the production of titanium metal powder (stage 7). R&D in both of these stages is developing novel local technologies which could be commercialised within the next decade. The individual roadmaps for each of these stages also consider alternative technological options such as the import of existing technologies in case the locally developed technologies are not commissioned on time or economically unfeasible.

- *Problem 2 - The ability to grasp market demand.*
  This problem was solved by recommending a market-pull roadmapping approach to ensure that the market South Africa is aiming for will be able to absorb the products planned to be produced. On each of the individual value chain roadmaps markets were indicated. The overall titanium metal industry roadmap elaborated on the markets for the two stages that produce titanium metal products namely stage 6 (mill products) and stage 8 (powder products). For stage 6 (mill products) the market is split between three industries namely the medical, chemical and aerospace industries. For stage 8 (powder products) the current market is split between the medical, aerospace and leisure industries but it is expected that the automotive industry will be added within the next three years.

- *Problem 3 - The construction of effective institutional mechanisms between supply and demand.*
  On the individual stage-specific roadmaps this problem was solved by considering sponge production (stage 4). The roadmapping exercise was able to illustrate that South Africa should not invest in a sponge plant as there is a global over-supply of the product and based on the large capital cost needed to establish this stage. South Africa also does not have access to the needed resources to establish this stage.

  Considering the overall South African titanium metal industry roadmap, this problem could be solved by considering the local production of $TiCl_4$ (stage 3). For this stage to be economically profitable a market locally and within Africa for $TiCl_4$ should be created within the next decade. This market should be able to take up the large quantities of the $TiCl_4$ that will be produced by the most likely technology route which is centred around imported technology. Implementing this technology route would also require the establishment of a local pigment industry. Establishing a pigment industry and gaining access to imported technology can only be done with the help of industrial partners and government aided incentives and policies.

2. **What would the roadmap for the South African titanium metal industry look like?**
   As this industry is fragmented several roadmaps were produced for this study. Firstly, seven roadmaps were produced to represent the individual stages of the identified titanium metal value chain (stage 1 and 2 were combined therefore only seven and not eight). An eighth and final roadmap was also constructed that indicated that the South African titanium metal value chain should remain fragmented (see Figure 49).

3. **What should the South African titanium metal industry vision be?**
   Based on the fragmented nature of the local titanium metal industry each stage of the titanium metal value chain has its own vision element. Mining of titanium mineral reserves and the upgrading of ilmenite into slag (stage 1 and 2) has a combined vision element as these two stages are generally combined in industry. The vision elements for the value chain stages can be viewed in Section 14.2.1.1. The overall vision for the South African titanium metal industry was developed by combining all of the vision elements. This vision is:

   South Africa should continue to mine and upgrade titanium mineral concentrates in a sustainable and efficient manner. The country should commit to the establishment of two additional stages within the titanium metal value chain which is $TiCl_4$ production and titanium metal powder production. Capacity and expertise within the two already developed downstream stages (mill product and powder product production) should be expanded for both the local and the export markets. Within the mill product market, the focus should be on producing products for the medical, chemical and aerospace industries while the powder product markets should focus on medical, aerospace, leisure and automotive industries.

4. **What does the global titanium metal value chain look like?**
   Globally only five countries have complete titanium metal value chains. These five countries are China, Kazakhstan, Russia, Ukraine and the USA. Only four of these countries are involved in every stage of the value chain

namely China, Kazakhstan, Russia and the USA. Ukraine does not produce titanium metal powder, but it does produce titanium metal following the sponge route. The remainder of the countries have fragmented titanium metal value chains. The six main reasons for fragmentation within the global titanium metal value chain are:

- complexity of the metal production process (also includes the cost of the process),
- purity of the mineral feedstock,
- environmental concerns,
- availability of the needed technology
- distance to the market, and
- absence of economic titanium reserves.

5. **Which stage(s) of the titanium metal value chain is South Africa involved in?**
South Africa is only involved in four of the eight stages of the titanium metal value chain. These are two upstream stages namely the mining of titanium minerals (stage 1) and the production of titanium slag by upgrading ilmenite (stage 2). The remaining two stages are in the downstream section of the value chain, namely the production of titanium mill products (stage 6) and the production of products from titanium metal powder (stage 8).

6. **Which stage(s) of the titanium metal value chain should South Africa focus on?**
According to the 10 year vision obtained from this study, South Africa is expected to add two additional value chain stages to its titanium industry by 2030. These stages are the production of $TiCl_4$ (stage 3) and the production of titanium metal powder (stage 7).

It is important to note that the existing stages should not be neglected. According to the vision the first two stages of the value chain, titanium mineral reserves and titanium slag production, will remain significant for the next decade. Stage 6 (mill product production) is expected to grow as local capabilities grow and the benefits of using titanium metal is accepted by industry. Stage 8 (titanium powder products) is part of a fast-growing AM industry and locally this stage is expected to grow as a supplier to the local and global markets. This means that South Africa should focus on six of the eight titanium metal value chain stages:

- the mining of titanium mineral reserves (stage 1),
- the upgrading of the minerals (stage 2),
- the production of $TiCl_4$ (stage 3),

- the production of mill products (stage 6),
- the production of titanium metal powder (stage 7), and
- the production of products from titanium metal powder (stage 8).

7. **With regards to the fragmented value chain in the titanium metal industry, should this value chain remain fragmented in South Africa?** The answer is yes. The South African titanium metal industry value chain should remain fragmented, at least for the next decade. South Africa should not establish the production of titanium sponge (stage 4) locally and not construct a titanium melting facility (stage 5) for the recommended 10 year value chain, see Figure 49.

14.4. Knowledge Contribution of this Research

New knowledge was added in understanding the fragmented value chain for the South African titanium metal industry. Although other logical value chains on the global and local titanium metal industry are available, this fragmented value chain layout was novel and designed for this research and its application. Roadmapping was applied as a tool to comment on the completeness of each stage of the titanium metal value chain. Prior to this research roadmapping was not applied on a fragmented value chain.

The research also leads to the increase in the body of knowledge in the methodology used to create a roadmap for an industry with a fragmented value chain. The methodology first required the establishment of a titanium metal industry value chain (based on global value chain). Each of the identified value chain stages were then subjected to the generic industry technology roadmap layout for market, product, technology, R&D and resources producing an independent roadmap for that specific stage. Based on the local requirements the vision elements for each of the value chain stages were either included or excluded from the overall South African titanium metal industry technology roadmap. Finally, inclusion and exclusion key aspects (developed from analysing six industry technology roadmaps) were developed that acted as a guide to produce the final roadmap section. This approach, where visioning is first done top-down, starting with individual value chain stage vision elements and then combined bottom-up to form an overall industry vision statement in the context of fragmentation in the industry value chain is a novel approach.

In summary the knowledge contributions were:

- the development of an industry titanium metal value chain,
- a roadmap for each stage of the titanium metal value chain,
- an overall South African titanium metal industry technology roadmap,

- inclusion and exclusion key aspects for research based roadmapping exercises (Section 3.1.2, Table 9 and Section 4.4.1, Table 13), and
- combining a top-down and bottom-up visioning process to activate a roadmap

This roadmap for the South African titanium metal industry is also the only roadmap produced solely on this metal. To the author's knowledge no roadmap covers only the titanium metal industry. In a literature search, roadmaps were obtained for other light metals such as aluminium. Roadmaps on AM and light metals (includes titanium and other metals) were obtained and discussed in the literature section of this research, but no roadmaps specifically on titanium were obtained.

In addition to the knowledge contributions, the outcomes of this research contribute to the South African titanium metal industry by developing a 10 year roadmap for the industry moving forward. As the roadmap considers both the current and future developments of industry as well as R&D, it could be used to evaluate and track the alignment of the business and R&D aspects in terms of technology, available markets, products being produced and the availability of resources. Ensuring a strong alignment would in turn encourage transparency, healthy competition and innovative advances.

14.5. Papers Emanating from this Research

From a literature perspective few scholars have addressed the fragmented nature of the value chain in the global titanium metal industry. As a result, the extent of global fragmentation was unknown. This research investigated the impact of fragmentation of the global titanium metal industry value chain the following papers were published:

1. A Systematic Literature Review On The Titanium Metal Product Value Chain published in the South African Journal of Industrial Engineering November 2019 Vol 30(3) Special Edition, pp 115-133 (Roux *et al*., 2019).
2. The fragmented nature of the titanium metal industry, submitted to the Journal of the South African Institute of Mining and Metallurgy (SAIMM), February 2020. In review.

14.6. Recommendations and Future Research

The development of an industry technology roadmap is only the first step of a continuous roadmapping process. Roadmaps should be tracked and updated as frequently as possible. It is therefore recommended that this roadmap be implemented by a governing body involved in developing the titanium metal industry and that this body appoints a custodian for the roadmap that can track and update it on a three-yearly basis.

Time and budget did not allow for this research to conduct a roadmapping workshop. It is therefore recommended that in future R&D such workshops are conducted and similar to this research, experts are included from both industry and R&D. It is recommended that separate workshops should be held for the upstream and downstream sections of the value chain. This recommendation is based on the knowledge gained in this study that the value chain covers a vast industry and that the downstream section of the value chain is not intimately involved in the upstream developments and vice versa. Separate workshops will ensure that enough time is spent on both upstream and the downstream without spending too much time explaining the primary concepts.

It is recommended that the methodology designed for this research, be applied to other fragmented industries to test its versatility and appropriateness. There is a wide array of fragmented industries that could be tested, but local examples include:

- clothing (textiles),
- electronics,
- agriculture, and
- retail and wholesale.

One of the key areas for future research falls under the vision element for $TiCl_4$ production within the next decade. The vision element obtained from the research indicated a need for this industry to be developed locally, but if a significant market for the $TiCl_4$ produced (by the recommended 100 ktpa plant) is not found, then building such a facility makes no sense. It is therefore recommended that the establishment of a titanium pigment plant (using the chlorination route) by 2030 should be investigated in more detail. The statement from interviewees that a 100 ktpa plant is required to be commercially viable needs to be confirmed for South African circumstances.

Although titanium scrap and the recycling thereof were only discussed briefly in this research, it is recommended that this be explored in more detail in South Africa as it was suggested that scrap processing could be feasible. A starting point for research in this field is obtaining the quantity and quality of scrap being produced. Once this is known, a better understanding of the needed purification and recycling platforms can be developed. An awareness campaign of recycling options and benefits is also recommended to inform titanium downstream users on the value of recycling.

14.7. Final Research Statement

A roadmap for the fragmented South African titanium metal value chain was produced. This roadmap indicates that the South African titanium metal value chain should remain fragmented for the next decade (2021 – 2030). Although the conclusion was that the value chain should remain fragmented, it should be expanded from four local stages established to six local stages established within this time period. The two stages that should be added are the production of $TiCl_4$ (stage 4) and the production of titanium metal powder (stage7). Two stages that should not be established in South Africa within the next decade are the production of titanium sponge (stage 4) and the production of titanium melted products (stage 6).

References

Abkowitz, S., Bannon, B., Broadwell, R., Harvey, B. and Broadwell, R., 1990. Titanium, The Choice. [online] Available at: <http://www.byterfly.eu/islandora/object/librib:110924/datastream/PDF/content/librib_110924.pdf> [Accessed 22 Oct. 2018].

Ahlqvist, T., Dufva, M., Kettle, J., Vanderhoed, N., Hytönen, E., Kivimaa, K., Valvovirta, V. and Loikkanen, T., 2013. Strategic roadmapping, industry renewal, and cluster creation: the case of cellulosic fibre value chain in the Green Triangle, South Australia. In: *6th ISPIM Innovation Symposium*. [online] Melbourne: ISPIM. Available at: <http://search.proquest.com/openview/d7acd6701f9270438de21a5a95fca99b/1?pq-origsite=gscholar&cbl=2040562>.

Amer, M., 2013. Extending Technology Roadmap through Fuzzy Cognitive Mapbased Scenarios: The Case of the Wind Energy Sector of Pakistan. [online] Portland State University. Available at: <https://pdfs.semanticscholar.org/39dc/9d2b8381ff7107731b03c4e56d9d4f523ce6.pdf?_ga=2.206807891.1743205920.1587816996-1381046869.1587816996>.

AMSC, 2017. Standardization Roadmap for Additive Manufacturing. [online] Available at: <https://www.mpif.org/News/TabId/164/ArtMID/586/ArticleID/144/Standardization-Roadmap-for-Additive-Manufacturing-20-Released.aspx> [Accessed 20 Jun. 2018].

ASDL, 2015. IATA Technology Roadmap. Technology Roadmap. [online] Available at: <www.iata.org> [Accessed 11 Sep. 2019].

Asian Metal, 2014. Titanium Sponge. [online] Available at: <http://metalpedia.asianmetal.com/metal/titanium/titaniumsponge.shtml> [Accessed 8 Jan. 2019].

Athukorala, P. and Yamashita, N., 2007. Production fragmentation in manufacturing trade: The role of East Asia in cross-border production networks. Working Papers Series No.003, (CCAS No.003).

AZoM, 2004. Titanium and Titanium Alloys - Superplastic Forming of Titanium Alloys. [online] Available at: <https://www.azom.com/article.aspx?ArticleID=2693> [Accessed 4 Dec. 2018].

Balinski, B., 2015. Manufacturers' Monthly Material of The Month Part 4: Titanium. [online] Manufacturers monthly. Available at: <https://www.manmonthly.com.au/features/manufacturers-monthly-material-of-the-month-part-4-titanium/> [Accessed 6 Feb. 2020].

Bam, W. and De Bruyne, K., 2017. Location policy and downstream mineral processing: A research agenda. The Extractive Industries and Society, 4, pp.443–447.

Belussi, F. and Sedita, S.R., 2010. Managing the fragmented value chain of global business: exploitative and explorative offshoring toward emerging market economies. In: The Past, Present and Future of International Business & Management. Emerald Group Publishing Limited.pp.399–429.

Bisaka, K., Thobadi, I. and Goso, X., 2016. Prereduction and DC open-arc smelting of carbon-based ilmenite pellets. In: *The Tenth Internation Heavy Minerals Conference*. [online] Sun City: Southern African Institute of Mining and Metallurgy.pp.159–172. Available at: <http://www.mintek.co.za/Pyromet/Files/2016 Bisaka2.pdf>.

Bodunrin, M.O., 2019. South Africa is one step closer to processed titanium alloys. [online] The Conversation. Available at: <https://theconversation.com/south-africa-is-one-step-closer-to-processed-titanium-alloys-122428> [Accessed 27 Nov. 2019].

Bolzoni, L., Ruiz-Navas, E.M. and Gordo, E., 2017. Quantifying the properties of low-cost powder metallurgy titanium alloys. Materials Science & Engineering A, [online] 687, pp.47–53. Available at: <https://csir.on.worldcat.org/oclc /6931338576>.

Bolzoni, L., Ruiz-Navas, E.M., Zhang, D.L. and Gordo, E., 2012. Modification of sintered titanium alloys by hot isostatic pressing. In: Key Engineering Materials. Trans Tech Publ.pp.63–69.

Bomberger, H.B. and Froes, F.H., 1984. The melting of titanium. JOM, 36(12), pp.39–47.

Bordbar, H., Yousefi, A.A. and Abedini, H., 2017. Production of titanium tetrachloride (TiCl4) from titanium ores : A review. Polyolefins Journal, 4(2), pp.149–173.

Botha, A.P., Pretorius, M.W., Govender, G. and Simpson, L., 2017. Developing an Industry Roadmap Model using Future Thinking and Business Model Integration. R&D Management Conference Proceedings 2017, pp.1–12.

Boyer, R., Welsch, G. and Collings, E.W., 2007. Materials Properties Handbook: Titanium Alloys. 4th ed. USA: ASM INternational. The Materials Information Society.

BusinessDictionary, 2018. Definition for Fragmented Industry. [online] Available at: <http://www.businessdictionary.com/definition/fragmented-industry.html> [Accessed 8 Apr. 2019].

BusinessDictionary, 2019. Forging definition. [online] Business Dictionary. Available at: <http://www.businessdictionary.com/definition/forging.html> [Accessed 27 Nov. 2019].

Businesstech, 2019. South Africa’s petrol and electricity prices vs the world. [online] Energy News. Available at: <https://businesstech.co.za/news/energy/306592 /south-africas-petrol-and-electricity-prices-vs-the-world/> [Accessed 17 Jan. 2020].

C11 Chlor-alkali, 2010. The South African Chlor-Alkali Industry. [online] Available at: <https://vula.uct.ac.za/access/content/group/9eafe770-4c41-4742-a414-

0df36366abe6/Chem Ind Resource Pack/html/learner-sheets/C/LS_C11.pdf> [Accessed 12 Apr. 2019].

Cambell, R., 2018. 3D printing surging globally and South Africa is making its mark. Engineering News. [online] Dec. Available at: <http://m.engineeringnews. co.za/article/3d-printing-is-surging-around-the-world-and-south-africa-is-making-its-mark-2018-12-07/rep_id:4433>.

Capus, J., 2016. Titanium Powder Metallurgy at POWDERMET 2015: past, present and future. Metal Powder Report, [online] 71(1), pp.25–27. Available at: <https://csir.on.worldcat.org/oclc/5898322032>.

Cardarelli, F., 2013. Materials Handbook. 3rd ed. Canada: Springer.

Carvalho, M.M., Fleury, A. and Lopes, A.P., 2013. An overview of the literature on technology roadmapping (TRM): Contributions and trends. Technological Forecasting and Social Change, [online] 80(7), pp.1418–1437. Available at: <http://dx.doi.org/10.1016/j.techfore.2012.11.008>.

Chang, I. and Zhao, Y., 2013. Advances in Powder Metallurgy - Properties, Processing and Applications. [online] Woodhead Publishing. Available at: <https://app.knovel.com/hotlink/toc/id:kpAPMPPA01/advances-in-powder-metallurgy/advances-in-powder-metallurgy>.

Chapman, G., 2016. Huntsman Announces Plan to Close its South African Titanium Dioxide (TiO2) Manufacturing Facility. [online] Available at: <https://www.huntsman.com/corporate/Applications/itemrenderer?p_rendertitle=no&p_renderdate=no&p_renderteaser=no&p_item_id=998075121&p_item_caid=1123> [Accessed 28 May 2019].

Chen, C.C., 1982. Recent Advancement in Titanium Near-Net-Shape Technology. JOM, [online] 34(11), pp.30–35. Available at: <https://csir.on.worldcat .org/oclc/5497194021>.

Cronje, J., 2020. SONA 2020: Business bodies welcome certainty on energy but plead for urgency. Fin24. [online] 14 Feb. Available at: <https://www.fin24.com/Economy/sona-2020-business-bodies-welcome-certainty-on-energy-but-plead-for-urgency-20200214>.

CSIR, 2019a. TITANIUM PILOT PLANT. [online] Research and Development. Available at: <https://www.csir.co.za/titanium-pilot-plant> [Accessed 11 Dec. 2019].

CSIR, 2019b. TITANIUM POWDERS PRODUCED AT THE CSIR EXPLORED FOR DOWNSTREAM PROCESSING. [online] Project Status: Ongoing. Available at: <https://www.csir.co.za/titanium-powders-produced-csir-explored-downstream-processing> [Accessed 11 Dec. 2019].

Daim, T. and Zahra, F., 2019. Industry 4.0 Value Roadmap. Integratin ed. [online] Springer London. Available at: <https://www.springer.com/gp/book/9783030300654#aboutBook>.

Daim, T.U., Oliver, T. and Phaal, R., 2018. Technology roadmapping. In: Technology Roadmapping. [online] pp.1–783. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85058890695&doi=10.1142%2F10859&partnerID=40&md5=e1a9f9fc7a02a3aca06e21863250d42a>.

De Cavin, M.P.S.F., 2012. An integrated framework for implementing technology roadmapping in industry. [online] University of Nottingham. Available at: <http://eprints.nottingham.ac.uk/12654/1/PhDThesis-SGMPdeCavin2012.pdf>.

De Laat, B., 2004. Conditions for effectiveness of roadmapping – a cross-sectoral analysis of 80 different roadmapping exercises. In: EU-US Seminar: New Technology Foresight, Forecasting & Assessment. [online] Seville.p.Paper 5. Available at: <Paper-5-conditions-for-effectiveness-of-roadmapping-a-cross-sectional-analysis-of-80-different-roadmapping-exercises-bastiaan-de-laat-40.html>.

Department of Energy, 2015. State of Renewable Energy in South Africa. [online] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Pretoria. Available at: <http://www.energy.gov.za/files/media/Pub/State-of-Renewable-Energy-in-South-Africa.pdf>.

Department of Energy, 2018. Integrated Resource Plan August 2018. [online] Government Notice. Pretoria. Available at: <http://www.energy.gov.za/IRP/irp-update-draft-report2018/IRP-Update-2018-Draft-for-Comments.pdf>.

Dewhurst, P., 2013. Titanium sponge supply, past, present and future. Titanium 2013, [online] October(Caesar's Palace), p.32. Available at: <https://cdn.ymaws.com/titanium.org/resource/resmgr/2010_2014_papers/DewhurstPhilipTiUSA2013Suppl.pdf>.

DF, G.D.F.G., 2015. FOR 8 MONTHS OF 2015, ZTMK HAS INCREASED PRODUCTION OF SPONGE TITANIUM BY 32.6%. Available at: <https://groupdf.com/uk/pres-tsentr/novini/za-8-misyatsiv-2015-ztmk-zbilshiv-virobnitstvo-titanu-gubchastogo-na-32-6/>.

DLR, 2013. IATA Technology Roadmap. [online] Available at: <https://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2013.pdf>.

DMR, 2011. A Beneficiation Strategy for the minerals industry of South Africa. [online] Johannesburg. Available at: <http://www.eisourcebook.org/cms/South Africa Mineral Beneficiation Strategy.pdf>.

Doblin, C., Freeman, D. and Richards, M., 2013. The TiROTM process for the continuous direct production of titanium powder. Key Engineering Materials, [online] 551. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84880086426&doi=10.4028%2Fwww.scientific.net%2FKEM.551.37&partnerID=40&md5=a41bfbf18df3f283ba258e212bc3553d>.

Donachie, M.J.J., 2000. Titanium. A Technical Guide. Second edi ed. Ohio: ASM International.

Dooley, G.J., 1975. Titanium production: ilmenite vs. rutile. Journal of Metals, 27(3), pp.8–16.

Du Preez, W., Damm, O. and Jordaan, J., 2013. Titanium Milled Products: Roadmap for SA. Pretoria: CSIR.

Du Preez, W.B., Damm, O.F.R.A. and Van Vuuren, D.S., 2012. Progress towards a Titanium Metal Industry for South Africa. In: 12th World Conference on Titanium, Ti 2011. [online] Materials Science and Manufacturing, CSIR, P O Box 395, Pretoria 0001, South Africa.pp.130–134. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0 84883119136&partnerID=40&md5=2429d4ba49a50846191f9b3e5da2a975>.

Durr, F.J.W., 2016. A Feasibility Study for Titanium Recycling in South Africa by. Stellenbosch University.

Durr, J.F.W. and Oosthuizen, G.A., 2016. A management framework for titanium recycling: A South African case study. In: P. L., T. G.A. and H. Y., eds. 25th International Association for Management of Technology Conference, IAMOT 2016. [online] Stellenbosch University, STC-LAM, Stellenbosch, 7600, South Africa: International Association for Management of Technology Conference (IAMOT) and the Graduate School of Technology Management, University of Pretoria.pp.393–407. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84988354865&partnerID=40&md5=e8ce89bb1aefdee905e83ca2fd7f3c7b>.

EIRMA, 1997. Technology Roadmapping: Delivering Business Vision. Working gr ed. Paris: European Industrial Research Management Association.

El Mir, H., Jardy, A., Bellot, J.-P., Chapelle, P., Lasalmonie, D. and Senevat, J., 2010. Thermal behaviour of the consumable electrode in the vacuum arc remelting process. Journal of Materials Processing Technology, 210(3), pp.564–572.

ENCA, 2019. Load-shedding could result in job losses, warns smelting industry. DStv news Channel. [online] 10 Dec. Available at: <http://enca.com/news/load-shedding-could-result-in-job-losses-warns-smelting-industry>.

Energetics Incorporate, 2017. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Titanium Manufacturing. [online] Communication, USA. Available at: <https://www.energy.gov/sites/prod/files/2017/12/f46/Titanium_bandwidth_study_2017.pdf>.

Energetics Incorporated, 2013. Measurement Science Roadmap for Metal-Based Additive Manufacturing. [online] Maryland. Available at: <https://www.nist.gov/system/files/documents/el/isd/NISTAdd_Mfg_Report_FINAL-2.pdf>.

EPA, U.S., 1995. Identification and Description of Mineral Processing Sectors and Waste Streams. [online] Available at: <https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/id4-ti.pdf>.

EPMA, 2004. Vision 2020. Future Developments for the European PM Industry. [online] Available at: <www.iom3.org/fileproxy/4033>.

EPMA, 2018. What is Powder Metallurgy? [online] Available at: <https://www.epma.com/what-is-powder-metallurgy> [Accessed 11 Sep. 2019].

Euiyoung, K., 2016. Design Roadmapping: Integrating Design Research Into Strategic Planning For New Product Development. University of California, Berkeley.

European Union Aviation Safety Agency, 2020. What is the definition of 'Critical parts'? [online] EASA website. Available at: <https://www.easa.europa .eu/faq/19013> [Accessed 19 Apr. 2020].

Fang, Z.Z., Paramore, J.D., Sun, P., Chandran, K.S.R., Zhang, Y., Xia, Y., Cao, F., Koopman, M. and Free, M., 2017. Powder metallurgy of titanium- past, present, and future. International Materials Reviews, 60 (7) pp.407-459.

Fangyuan Titanium Industry, 2020. How to manufacture titanium dioxide by chloride process. [online] Tio2 FR-761. Available at: <http://www.fangyuan-tio2.com/how-to-manufacture-titanium-dioxide-by-chloride-process.html>.

Fine, C., 2004. Roadmapping the Communications Value Chain. MIT Center for eBusiness, III(2).

Froes, F., Gungor, M. and Imam, M.A., 2007. Cost-affordable titanium: The component fabrication perspective. JOM, [online] 59(6), pp.28–31. Available at: <https://csir.on.worldcat.org/oclc/440503898>.

Froes, F.H., 2015a. Melting, Casting, and Powder Metallurgy. In: F.H. Froes, ed. Titanium—Physical Metallurgy, Processing, and Applications. ASM International.pp.161–182.

Froes, F.H., 2015b. Titanium - Physical Metallurgy, Processing, and Applications. [online] Materials Park, OH, USA: ASM International. Available at: <https://app.knovel.com/hotlink/toc/id:kpTPMPA00D/titanium-physical-metallurgy/titanium-physical-metallurgy>.

Gabriele, M., 2018. Titanium usa 2018, Executive Summary. In: Titanium USA 2018. [online] Internation Titanium Association (ITA).pp.1–40. Available at: <https://cdn.ymaws.com/titanium.org/resource/resmgr/02_jens_folder/titanium_usa_2018_executive_.pdf>.

GeoscienceAustralia, 2019. Applying geoscience to Australia's most important challenges. [online] Australian Government. Available at: <http://www.ga. gov.au/education/classroom-resources/minerals-energy/australian-mineral-facts/titanium> [Accessed 13 May 2019].

German, R.M., 2010. STATUS OF METAL POWDER INJECTION MOLDING OF TITANIUM. International Journal of Powder Metallurgy, [online] 46(5), pp.11–17. Available at:

<http://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,uid,cookie&db=egs&AN=54617560&site=ehost-live>.

Ghobakhloo, M., 2018. The future of manufacturing industry: a strategic roadmap toward Industry 4.0. Journal of Manufacturing Technology Management, [online] 29(6), pp.910–936. Available at: <www.emeraldinsight.com/1741-038X.htm>.

Goso, X. and Kale, A., 2011. Production of titanium metal powder by the HDH process. Journal of the Southern African Institute of Mining and Metallurgy, 111(3), pp.203–210.

Govender, S., 2017. CSIR interventions in the field of light metals set to benefit SMMEs. Sciencescope, 11(2).

Grand View Research, 2019. Titanium Dioxide (TiO2) Market Size, Share & Trends Analysis Report By Application (Paints & Coatings, Plastics, Pulp & Paper, Cosmetics), By Region (North America, Europe, APAC, MEA, CSA), And Segment Forecasts, 2019 - 2025. [online] Available at: <https://www.grandviewresearch .com/industry-analysis/titanium-dioxide-industry>.

Greyling, L., 2019. Personal Communication. [online] Available at: <Personal> [Accessed 24 Sep. 2019].

Haddad, C.R. and Maldonado, M.U., 2017. A functions approach to improve sectoral technology roadmaps. Technological Forecasting and Social Change, [online] 115, pp.251–260. Available at: <http://dx.doi.org/10.1016/j. techfore.2016.08.006>.

Henriques, V.A.R., Sandim, H.R.Z. and Da Silva, C.R.M., 2003. Use of Titanium Powders Obtained by Sponge Screening and for the HDH Process in Titanium Alloy Production for Powder Metallurgy (P/M). Materials Science Forum, [online] 1(416–418), pp.23–28. Available at: <https://www.ipen.br/biblioteca /cd/ptech/ 2001/1_08.PDF>.

Hockaday, S.A.C. and Bisaka, K., 2010. Experience and Results from running of a 1kg Ti scale Kroll Reactor. The Southern African Institute of Mining and Metallurgy, Advanced Metals Initiative: Light Metals Conference 2010, pp.265–280.

ICMM, 2020. The ‘circular economy’ in mining and metals. [online] Mining with Principles. Available at: <https://miningwithprinciples.com/the-circular-economy-in-mining-and-metals/> [Accessed 4 Apr. 2020].

ILUKA, 2019. Mineral Sands Industry Information. [online] Available at: <https://www.iluka.com/CMSPages/GetFile.aspx?guid=bd24ecdc-5b71-4681-9340-87c85555cca5>.

InForGrowth, 2019. Global Titanium (IV) Chloride (TiCl4) market will grow at a healthy CAGR of 4.2% by 2025 according to new research report. [online] WhaTech Channel: Materials and Chemicals. Available at: <https://www.whatech.com/ market-research/materials-chemicals/583134-global-titanium-iv-chloride-ticl4-market-will-grow-at-a-healthy-cagr-of-4-2-by-2025> [Accessed 6 Feb. 2020].

IPAP, 2014. Industrial Policy Action Plan. [online] Pretoria. Available at: <https://www.idc.co.za/wp-content/uploads/2019/02/IPAP2014.pdf>.

IPAP, 2017. Industrial Policy Action Plan, 2017/18-2019/20. [online] Pretoria, South Africa. Available at: <https://www.gov.za/sites/default/files/IPAP1718_1920.pdf>.

Ivasishin, O., 2006. Cost-effective Production of Powder Metallurgy Titanium components. [online] Slide Player. Available at: <https://slideplayer.com/slide/751287/> [Accessed 8 Jan. 2019].

Jackson, B., 2019. MINING COMPANY PRG BUYS METALYSIS OUT OF ADMINISTRATION. [online] 3D Printing Industry. Available at: <https://3dprintingindustry.com/news/mining-company-prg-buys-metalysis-out-of-administration-158237/> [Accessed 9 Dec. 2019].

Jackson, M., 2007. Titanium 21st Century. Materials World, Imperial C(May), pp.32–34.

Ji, S., 2013. Quantification of the Heat Transfer during the Plasma Arc Remelting of Titanium Alloys. [online] University of British Columbia. Available at: <open.library.ubc.ca>.

Johnson, S., 2016. The Product Roadmap vs. the Technology Roadmap. [online] Aha Blog. Available at: <https://blog.aha.io/the-product-roadmap-vs-the-technology-roadmap/> [Accessed 4 Mar. 2019].

Kale, A. and Bisaka, K., 2016. Review of titanium feedstock selection for fluidized bed chlorinators. In: The Tenth Internation Heavy Minerals Conference. [online] Sun City: Southern African Institute of Mining and Metallurgy.pp.313–324. Available at: <http://www.mintek.co.za/Pyromet/Files/2016Kale.pdf>.

Kale, A. and Hockaday, L., 2018. Personal communication. [online] Available at: <Personal> [Accessed 24 Apr. 2019].

Kerr, C. and Phaal, R., 2015. Visualizing roadmaps: A design-driven approach. Research Technology Management, 58(4), pp.45–54.

Kosemura, S., Fukasawa, E., Ampo, S., Shiraki, T. and Sannohe, T., 2002. Technology trend of titanium sponge and ingot production. Nippon Steel Technical Report, [online] (85), pp.31–35. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0036252969&partnerID=40&md5=c82162ba73f16ee4256bb0b6d0f18776>.

Kostoff, R.N. and Schaller, R.R., 2001. Science and technology roadmaps. IEEE Transactions on Engineering Management, [online] 48(2), pp.132–143. Available at: <https://www.researchgate.net/publication/3076681_Science_and_technology_roadmaps_IEEE_Trans_Eng_Manag>.

Kotzé, H., Bessinger, D. and Beukes, J., 2006. Ilmenite smelting at Ticor SA. Journal of the Southern African Institute of Mining and Metallurgy, [online] 106(3), pp.165–170. Available at: <https://www.saimm.co.za/Conferences/Pyro2006/203_Ticor.pdf>.

Letaba, T.P., 2018. Complex Technology Roadmap Development in the Context of Developing Countries. University of Pretoria.

Li, X.D., Hong, W., Liu, N. and Geng, L.X., 2013. Establishment research on industry technology roadmapping for technology innovation. Applied Mechanics and Materials, [online] 321–324. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84879753375&doi=10.4028%2Fwww.scientific.net%2FAMM.321-324.2363&partnerID=40&md5=35e835f9e3e12603cf0c233eb8d41ddc>.

Liu, Q., Li, X. and Jiang, Y., 2017. Numerical simulation of EBCHM for the large-scale TC4 alloy slab ingot during the solidification process. Vacuum, 141, pp.1–9.

Liu, R., Wang, Z., Sparks, T., Liou, F. and Newkirk, J., 2017. Aerospace applications of laser additive manufacturing. In: M. Brandt, ed. Laser Additive Manufacturing, A volume i. [online] Materials, Design, Technologies, and Applications: Woodhead Publishing.pp.351–371. Available at: <https://www.sciencedirect.com/science/article/pii/B9780081004333000130>.

Londo, H.M., More, E., Phaal, R., Wütenberger, L. and Cameron, L., 2013. Background Paper on Technology Roadmaps. In: Report for United Nations Framework Convention on Climate Change (UNFCCC). Technology Executive Committee of the United Nations Framework Convention on Climate Change.

Lu, X., Hiraki, T., Nakajima, K., Takeda, O., Matsuabe, K., Zhu, H.-M., Nakamura, S. and Nagasaka, T., 2012. Thermodynamic analysis of separation of alloying elements in recycling of end-of-life titanium products. Separation and Purification Technology, [online] 89, pp.135–141. Available at: <https://csir.on.worldcat.org/oclc/5901370982>.

Manitoba Aerospace, 2017. Manitoba Aerospace Technology Roadmap. [online] Available at: <http://www.westcard.ca/wp-content/uploads/2017/07/MB-Aerospace-Road-Map-Summary_2017Final_smallfilesize.pdf>.

Mankins, J.., 1995. Technology readiness levels. Research Technology Management, [online] Advanced C(6 April). Available at: <https://aiaa.kavi.com/apps/group_public/download.php/2212/TRLs_MankinsPaper_1995.pdf>.

Market Reports, 2019. Titanium Tetrachloride (TiCl4) Market Detailed Analytical Overview by 2029. [online] Consumer Report Review. Available at: <https://consumerreportsreview.com/titanium-tetrachloride-market-detailed-analytical-overview-by-2029/> [Accessed 3 Jul. 2019].

Martin, H. and Daim, T.U., 2012. Technology roadmap development process (TRDP) for the service sector: A conceptual framework. Technology in Society, [online] 34(1), pp.94–105. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0160791X12000048>.

Matsuoka, R., Mineta, K. and H, T.O., 2004. Recycling process for tantalum and some other metal scraps. The Minerals, Metals & Materials Society, (EPD Congress).

McCracken, C.G., Motchenbacher, C. and Barbis, D.P., 2010. Review of titaniumpowder-production methods. International Journal of Powder Metallurgy (Princeton, New Jersey), [online] 46(5), pp.19–26. Available at: <https://csir.on.worldcat.org/oclc/694418201>.

Menezes, P.., Reeves, C.., Kailas, S.. and Lovell, M.., 2013. Tribology in Metal Forming. Tribology for Scientists and Engineers, [online] (Springer, NY), pp.783–818. Available at: <https://link.springer.com/chapter/10.1007/978-1-4614-1945-7_24>.

Meng, B. and Miroudot, S., 2011. Towards measuring trade in value-added and other indicators of global value chains: Current OECD work using I/O tables. In: Global Forum on Trade Statistics. Geneva: OECD and IDE-JETRO.

Motsie, R., 2008. An overview of South Africa’s titanium mineral concentrate industry. [online] Directorate Mineral Economics. Available at: <http://www .dmr.gov.za/LinkClick.aspx?fileticket=Yp939PhQ8lQ%3D&portalid=0>.

Moxson, V.S., Senkov, O.N. and Froes, F.H., 2000. Innovations in titanium powder processing. Journal of Minerals, Metals and Materials Scociety, 52(5), pp.24–26.

Moyer, J.M., Jackman, L.A., Adasczik, C.B., Davis, R.M., Forbes-Jones, R. and Allvac, T., 1994. Advances in Triple Melting Superalloys 718, 706 and 720. Superalloys 718, 625, 706 and Various Derivatives, pp.39–48.

MPIF, 2012. PM Industry Roadmap, Technology Update for the Powder Metallurgy Industry. [online] Available at: <https://www.asminternational.org/documents /20457020/21205929/Powder+Metallurgy+Industry+Roadmap+2012.pdf/75de0b4 7-262a-4de5-bda4-e97d5e496e0b>.

Nagesh, C., Sridhar Rao, C., Ballal, N.B. and Krishna Rao, P.K., 2004. Mechanism of titanium sponge formation in the kroll reduction reactor. METALLURGICAL AND MATERIALS TRANSACTIONS B-PROCESS METALLURGY AND MATERIALS PROCESSING SCIENCE, 35(1), pp.65–74.

Nagesh, R.V.S., Ramachandran, C.S. and Subramanyam, R.B., 2008. Methods of titanium sponge production. Transactions of the Indian Institute of Metals, [online] 61(5), pp.341–348. Available at: <https://csir.on.worldcat.org/oclc/5652759987>.

Nedbank, 2019. Annual Average Exchange Rates-Nedbank. [online] South Africa. Available at: <https://www.nedbank.co.za/content/dam/nedbank/site-assets/ AboutUs/Economics_Unit/Forecast_and_data/Daily_Rates/Annual_Average_Exch ange_Rates.pdf>.

Neikov, O.., Naboychenko, S.. and Yefimov, N.., 2019. Production of Refractory Metal Powders. In: I.. Frishberg, O.. Neikov, D.. Lotsko, S. Naboychenko, V.. Gopienko and I. Mourachova, eds. Handbook of Non-Ferrous Metal Powders, 2ed ed. [online] Yekaterinburg, Russia: Elsevier.pp.685–755. Available at: <https://www.sciencedirect.com/science/article/pii/B9780081005439000233>.

Nyanza Light Metals, 2017. Nyanza Light Metals plant will produce titanium dioxide pigment for Africa. Additives for Polymers, [online] 2017(7), p.7. Available at: <https://reader.elsevier.com/reader/sd/pii/S0306374717301148?token=B013637F31365608862206A574F5596921E5A2E21650192910197A1C7971908748003D4117B81A8E80CA37CDBCC0C1EC>.

Oh, J.-M., Roh, K.-M., Lee, B.-K., Suh, C.-Y., Kim, W., Kwon, H. and Lim, J.-W., 2014. Preparation of low oxygen content alloy powder from Ti binary alloy scrap by hydrogenation–dehydrogenation and deoxidation process. Journal of Alloys and Compounds, 593, pp.61–66.

Okabe, T.H., Oda, T. and Mitsuda, Y., 2004. Titanium powder production by preform reduction process (PRP). Journal of Alloys and Compounds, [online] 364(1–2), pp.156–163. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-0348039908&doi=10.1016%2FS0925-8388%2803%2900610-8&partnerID=40&md5=ab914c6bb6e5293adaf99a82596c5000>.

Oosthuizen, S.J.J. and Swanepoel, J.J.J., 2018. Development status of the CSIR-Ti Process. In: C. S. and M. R., eds. 2018 Conference of the South African Advanced Materials Initiative, CoSAAMI 2018. [online] Council for Scientific and Industrial Research, Advanced Materials and Engineering, Meiring Naude Road, Pretoria, 0184, South Africa: Institute of Physics Publishing. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85054784784&doi=10.1088%2F1757-899X%2F430%2F1%2F012008&partnerID=40&md5=2f54d61741ab25606a8b3309e49552f0>.

OSAKA, T.T., 2018. Titanium Sponge. [online] Available at: <http://www.osaka-ti.co.jp/e/e_product/titan/sponge.html> [Accessed 9 Mar. 2019].

Osypenko, O., 2015. Development of technology of obtaining raw materials for titanium alloys made of off-grade titanium sponge. EasternEuropean Journal of Enterprise Technologies, 4(5), pp.28–32.

Paton, B.E., Trigub, N.P. and Zhuk, G. V, 2008. Crystallization of titanium ingots in the course of electron-beam melting. Materials Science, [online] 44(3), pp.328–335. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-57649188848&doi=10.1007%2Fs11003-008-9090-2&partnerID=40&md5=167dc9fdd7f1d2a483d597486655ebf2>.

Phaal, R., 2015a. Roadmapping for innovation, strategy and policy. Centre for Technology Management, internal, October (Centre of Technology Management class presentation).

Phaal, R., 2015b. Roadmapping for strategy and innovation. In: IEE Seminar on justifying and selecting innovation projects. Centre for Technology Management Institute for Manufacturing, University of Cambridge.pp.1–7.

Phaal, R., 2016. Technology Roadmapping. In: B. Römgens, ed. Foresight in Organizations: Methods and Tools. University of Cambridge: Centre for Technology Management.pp.145–168.

Phaal, R., 2020a. Architecting roadmaps. [online] Cambridge Roadmapping. Available at: <https://www.cambridgeroadmapping.net/architecting> [Accessed 4 Apr. 2020].

Phaal, R., 2020b. Roadmapping for strategy and innovation. Education and Consultancy Services- IfM, University of Cambridge. Department of Engineering.

Phaal, R., Farrukh, C.J.P. and Probert, D.R., 2001. Characterisation of technology roadmaps: purpose and format. In: Portland International Conference on Management of Engineering and Technology. Proceedings Vol. 1: Book of Summaries (IEEE Cat. No. 01CH37199). Portland: IEEE.pp.367–374.

Phaal, R., Farrukh, C.J.P. and Probert, D.R., 2004. Technology roadmapping—a planning framework for evolution and revolution. Technological forecasting and social change, 71(1–2), pp.5–26.

Phaal, R., Farrukh, C.J.P. and Probert, D.R., 2005. Developing a technology roadmapping system. In: Portland International Conference on Management of Engineering and Technology. [online] pp.99–111. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-33748859860&doi=10.1109%2FPICMET.2005.1509680&partnerID=40&md5=42f1d98b0db758a2afd6344ff5b745a9>.

Pistorius, P.C., 2008. Ilmenite smelting: The basics. Journal of the Southern African Institute of Mining and Metallurgy, 108(1), pp.35–43.

Potgieter, J.. and Van der Lingen, E., 2016. Noble Metal Additions to Passive Alloys: Effect on Corrosion Resistance. Reference ed. Oxford: Elsevier.

QuantecEasyData, 2019. ANNUAL IMPORT FIGURES FOR TITANIUM. 2019 trade data. [online] RSA Trade data. Available at: <Institutional download>.

QY Research Group, 2017. Global Titanium Powder Market Research Report 2017. [online] Available at: <http://www.reportsnreports.com/reports/800353-global-titanium-powder-market-research-report-2017.html>.

Raj, G. and Farrow, S., 1987. Titanium Recycling. Journal of the Washington Academy of Sciences, [online] 77(4), pp.126–129. Available at: <https://csir.on.worldcat.org/oclc/7025426811>.

RAPDASA, 2016. A South African Additive Manufacturing Strategy. [online] Pretoria, South Africa. Available at: <https://site.rapdasa.org/wp-content/uploads/2017/02/South-African-Additive-Manufacturing-Strategy.pdf>.

Reporter, S., 2018. Highveld Steel ticks over, gearing up to rise once again. [online] Mail & Guardian. Available at: <https://mg.co.za/article/2018-02-09-00-highveld-steel-ticks-over-gearing-up-to-rise-once-again/> [Accessed 17 Jan. 2019].

Reports&Data, 2019. Additive Manufacturing Market To Reach USD 23.33 Billion By 2026. [online] West. Available at: <https://www.globenewswire.com/news-release/2019/03/18/1756526/0/en/Additive-Manufacturing-Market-To-Reach-USD-23-33-Billion-By-2026.html> [Accessed 9 Dec. 2019].

RéseauTrans-Al, 2006. Canadian Aluminium Transformation Technology Roadmap. Complete version. [online] Canada. Available at: <ISBN 978-2-9809883-1-8>.

Roberts, J., 2018. Titanium metal- what will the next decade bring? Titanium USA 2018, [online] October 7-(USA). Available at: <https://www.youtube.com/watch?v=tc9_pHKQ8gI>.

Rokita, P.S., 2017. Socio-economic and Techno-economic Factors Associated with Establishing a Titanium Machining Industry in South Africa, a Qualitative Study. Stellenbosch University.

Roskill, 2019. Titanium Metal: Outlook to 2029. Ninth Edition. [online] Wimbledon. Available at: <https://www.roskillinteractive.com/reportaction/TIM9/Toc>.

Roskill reports, 2013. Titanium Metal: Market Outlook to 2018. Sixth Edition. Sixth Edition. Wimbledon.

Roux, N., Van der Lingen, E., Botha, A.P. and Botes, A., 2019. Fragmentation within the titanium industry. In: CoSAami 2019. [online] Vanderbijl Park: Mintek. Available at: <Unpunlished>.

Roux, R.N., Van der Lingen, E. and Botha, A.P., 2019. A systematic literature review on the titanium metal product value chain. South African Journal of Industrial Engineering, 30(3), pp.115–133.

SAAIR, 2017. The South African Aluminium Industry Roadmap. [online] Pretoria. Available at: <http://www.afsa.org.za/Downloads/South-African-Aluminium-Industry-Roadmap-2017.pdf>.

Sandenbergh, R. and Van der Lingen, E., 2005. The use of Tafel back extrapolation to clarify the influence of ruthenium and palladium alloying on the corrosion behaviour of titanium in concentrated hydrochloric acid. Corrosion Science, 47, pp.3300–3311.

Saunders, M., Lewis, P. and Thornhill, A., 2016. Research Methods for Business Students. Seventh ed. England: Pearson Education Limited.

Sawant, A., 2018. Titanium Ore Market Size 2018 Industry Growth, Demand Structure, Product Analysis, New Developments, Prominent Key Players, Competitive Analysis Research Report 2023. M2PressWIRE Research Report. [online] 10 Jan. Available at:

<http://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,uid,cookie&db=nfh&AN=16PU473534371&site=ehost-live.>.

Science_Scope, 2018. Infrastructure in support of industry. [online] Pretoria, South Africa. Available at: <https://www.csir.co.za/sites/default/files/Documents/CSIR Science Scope Vol 13 no 1.pdf>.

Services, R.I., 2017. Titanium Metal Market Emerges From Past Excesses with More Changes Anticipated - Roskill Information Services. Available at: <https://www.prnewswire.com/news-releases/titanium-metal-market-emerges-from-past-excesses-with-more-changes-anticipated---roskill-information-services-621421953.html>.

Simpson, T.W., 2018. Why Does My 3D-Printed Part Cost So Much? [online] Additive Manufacturing. Available at: <https://www.additivemanufacturing.media/blog/post/why-does-my-3d-printed-part-cost-so-much> [Accessed 8 Jan. 2019].

Smartsheet, 2019. Everything You Need to Know about Project Roadmaps. [online] online. Available at: <https://www.smartsheet.com/answers-all-your-project-roadmap-questions> [Accessed 5 Mar. 2019].

Smith, S., 2018. The global additive manufacturing market is expected to grow to US$ 36.61 billion by 2027 from US$ 8.44 billion in 2018. [online] Market Research Report. Available at: <https://www.prnewswire.com/news-releases/the-global-additive-manufacturing-market-is-expected-to-grow-to-us-36-61-billion-by-2027-from-us-8-44-billion-in-2018--300810990.html> [Accessed 6 Jan. 2020].

Tang, Y., Li, C., Zeng, L., Wang, Z. and Hu, X., 2009. Technology road-mapping for local industrial value chain upgrading: A preliminary framework. In: 16th International Conference on Industrial Engineering and Engineering Management. Beijing, 21-23 October: IEEE.pp.945–949.

Tarselli, M.A., 2013. Titanium tales. Nature chemistry, 5(6), p.546.

The Aluminum Association, 2003. Aluminum Industry Technology Roadmap. [online] Washington, D.C. Available at: <www.aluminum.org>.

Titanium Institute, 2019. Pilot Plant and its Products. [online] Timag.org. Available at: <http://timag.org/en/we-produce/> [Accessed 15 May 2019].

Tong, R. and Li, C., 2011. Industry technology roadmapping research based on consensus system emergence modeling. In: International Conference on Management and Service Science, MASS 2011. [online] Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-80052873197&doi=10.1109%2FICMSS.2011.5997934&partnerID=40&md5=21798c1ce81b1f26c0125e559f43ddf2>.

Total-Materia, 2007a. Forming of the Titanium and Titanium Alloys: Part One. [online] The world’s most comprehensive materials database. Available at: <https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=165> [Accessed 27 Nov. 2019].

Total-Materia, 2007b. Forming of Titanium and Titanium Alloys: Part Two. [online] The world's most comprehensive materials database. Available at: <https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=KTN&NM=167> [Accessed 27 Nov. 2019].

Total Materia, 2018. Titanium Standards. [online] Available at: <https://www.totalmateria.com/page.aspx?ID=TitaniumStandards&LN=EN> [Accessed 9 Apr. 2018].

Tronox, 2020. Personal communication. Pretoria.

Tyler, R.M. and Minnittt, R.C.A., 2004. A review of sub-Saharan heavy mineral sand deposits: Implications for new projects in southern Africa. Journal of The South African Institute of Mining and Metallurgy, [online] 104(2), pp.89–99. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-2542453991&partnerID =40&md5=f69ae491c0afe025ac461ddc3cda99cc>.

TZMI, 2012. TiO2 feedstock annual review. [online] Victoria Park WA. Available at: <http://www.prweb.com/releases/2012/7/prweb9656188.htm>.

USGS, 2018. Mineral Commodity Summaries. [online] Available at: <https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf>.

USGS, 2019. Titanium Mineral Concentrates. [online] United States of America. Available at: <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-titanium-minerals.pdf>.

Vardelle, A., Moreau, C., Akedo, J., Ashrafizadeh, H., Berndt, C.C., Berghaus, J.O., Boulos, M., Brogan, J., Bourtsalas, A.C., Dolatabadi, A., Dorfman, M., Eden, T.J., Fauchais, P., Fisher, G., Gaertner, F., Gindrat, M., Henne, R., Hyland, M., Irissou, E., Jordan, E.H., Khor, K.A., Killinger, A., Lau, Y.-C., Li, C.-J., Li, L., Longtin, J., Markocsan, N., Masset, P.J., Matejicek, J., Mauer, G., McDonald, A., Mostaghimi, J., Sampath, S., Schiller, G., Shinoda, K., Smith, M.F., Syed, A.A., Themelis, N.J., Toma, F.-L., Trelles, J.P., Vassen, R. and Vuoristo, P., 2016. The 2016 Thermal Spray Roadmap. Journal of Thermal Spray Technology, 25(8), pp.1376–1440.

Van der Lingen, E. and Sandenbergh, R., 2001. The cathodic modification behaviour of ruthenium additions to titanium in hydrochloric acid. Corrosion Science, 43, pp.577–590.

Van der Lingen, E. and Steyn, H., 1994. The Potential of Ruthenium as an Alloying Element in Titanium, Proceedings of the 1994 International Conference on Titanium Products and Applications, (San Diego: TDA), pp. 450-458.

Van Tonder, W., 2010. SOUTH AFRICAN TITANIUM: Techno- Economic Evaluation of Alternatives to the Kroll Process. Stellenbosch University.

Van Vuuren, D.S., 2009a. A critical evaluation of processes to produce primary titanium. Journal of the Southern African Institute of Mining and Metallurgy, [online] 109(8), pp.455–461. Available at: <https://www.scopus .com/inward/record.uri?eid=2-s2.0-73849101378&partnerID=40&md5=62f00de8 b02ca6c73f3b21857552baf1>.

Van Vuuren, D.S., 2009b. Keynote address : Titanium — an opportunity and challenge for. In: The 7th International Heavy Minerals Conference 'What next'. The Southern African Institute of Mining and Metallurgy.pp.1–8.

Vermeulen, M., 2018. Aeroswift. [online] Online. Available at: <https://camasa.co.za/wp-content/uploads/2018/02/Aeroswift.pdf> [Accessed 9 Sep. 2019].

Wang, Z., Li, J., Hua, Y., Zhang, Z., Zhang, Y. and Ke, P., 2014. Research progress in production technology of titanium. Xiyou Jinshu/Chinese Journal of Rare Metals, [online] 38(5), pp.915–927. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84919827973&doi=10.13373%2Fj.cnki.cjrm.2014.05.026&partnerID=40&md5=bac6f8eeec3767967b63abab9e534a2d>.

WBCSD, 2018. SDG Sector Roadmaps. [online] Gemeva. Available at: <https://www.wbcsd.org/Programs/People/Sustainable-Development-Goals/SDG-Sector-Roadmaps>.

Whalen, P.J., 2007. Strategic and technology planning on a roadmapping foundation. Research-Technology Management, [online] 50(3), pp.40–51. Available at: <https://www.tandfonline.com/doi/abs/10.1080/08956308.2007.11657440>.

Whitelock, D. and Brasher, A., 2006. Developing a Roadmap for e-Assessment: Which way now? Proceedings of the 10th CAA International Computer Assisted Assessment Conference, [online] 10th, pp.487–501. Available at: <http://www.caaconference.com/pastConferences/2006/proceedings/index.asp>.

Whittaker, D., 2012. Powder processing, consolidation and metallurgy of titanium. Powder Metallurgy, [online] 55(1), pp.6–10. Available at: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84859727703&doi=10.1179%2F174329012X13297486041231&partnerID=40&md5=4902e52aedaa032de2573254d7bfae03>.

Wohlers Associates, I., 2011. Additive Manufacturing. Technology Roadmap for Australia. [online] Available at: <http://3dprintingexpo.org/wp-content/uploads/Additive-Manufacturing-Technology-Roadmap-CSIRO-2011.pdf>.

Woodruff, L. and Bedinger, G., 2013. Titanium—Light, Strong, and White. Fact Sheet 201, [online] 3059(August), pp.1–2. Available at: <https://pubs.usgs.gov/fs/2013/3059/>.

Zhang, D., Raynova, S., Nadakuduru, V., Cao, P., Gabbitas, B. and Robinson, B., 2009. Consolidation of titanium, and Ti-6Al-4V alloy powders by powder compact forging. Materials Science Forum, 618 619(April), pp.513–516.

Zhao, Y.X., Gao, B.Y., Zhang, G.Z. and Qi, Q.B., 2014. Coagulation and sludge recovery using titanium tetrachloride as coagulant for real water treatment: A comparison against traditional aluminum and iron salts. Separation and Purification Technology, [online] 130(June), pp.19–27. Available at: <https://www.researchgate.net/publication/262019814_Coagulation_and_sludge_recovery_usin

g_titanium_tetrachloride_as_coagulant_for_real_water_treatment_A_comparison_against_traditional_aluminum_and_iron_salts>.

Zheng, H. and Okabe, T.H., 2008. Recovery of titanium metal scrap by utilizing chloride wastes. Journal of Alloys and Compounds, [online] 461(1), pp.459–466. Available at: <https://csir.on.worldcat.org/oclc/4933115847>.

15. Appendices

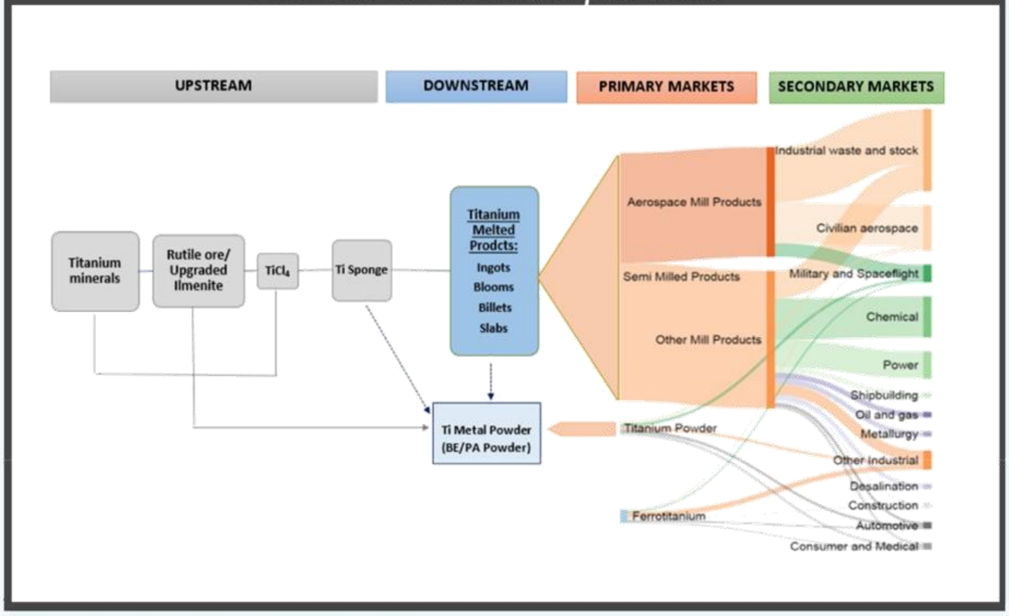
15.1. Appendix A: Interviewee Information Flyer

#1

INFORMATION SHEET

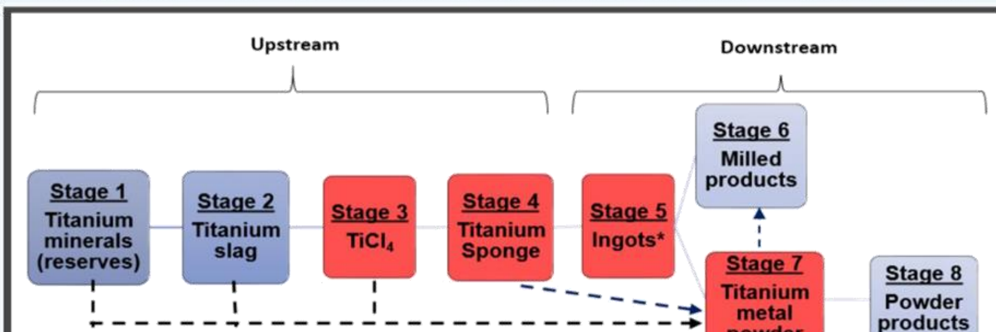
A roadmap for the titanium industry of South Africa

Markets for titanium products



1. The titanium metal value chain

For the purpose of this research the titanium value chain has been divided into eight production stages. Each stage is dependent on its specific precursor that in turn is needed to produce the product for the next stage. This outlines the titanium metal product value chain and is displayed in the figure below. The dotted lines indicate alternative routes that can be followed to produce the final stages, loosely referred to as milled products and powder products. Globally only four countries have a complete titanium metal value chain namely USA, China, Kazakhstan and Ukraine. South Africa does not have a complete titanium metal value chain and only four of the eight stages are developed on industry level (in blue).



(From :Roux, Van der Lingen and Botha, 2019)

- **Stage 1:** South Africa has the fourth most titanium reserves in the world.
- **Stage 2:** South Africa exports upgraded/purified ore.
- **Stage 6:** Several local companies are machining imported ingots, blooms, billets or slabs into final products. These products are then sold to either the local or international market.
- **Stage 8:** Local companies are fabticating specialised parts from titanium powder.

Compiled by Nicolene Roux for PhD studies in Technology Management and Innovation
In collaboration with the CSIR and the University of Pretoria
For more information contact Nicolene at nroux@csir.co.za

#2 INFORMATION SHEET

2. The titanium industry and markets

Most of the commercially produced titanium products are mill products (mainly for the use in aerospace), ferrotitanium products and products obtained from titanium metal powder (Roberts, 2018). Proportionally the milled product market is the biggest, followed by the ferrotitanium market and lastly the titanium metal powder market (Roberts, 2018).

The table towards the right indicates the most popular titanium industries accompanied with the reasons for the use of titanium metal in these industries.

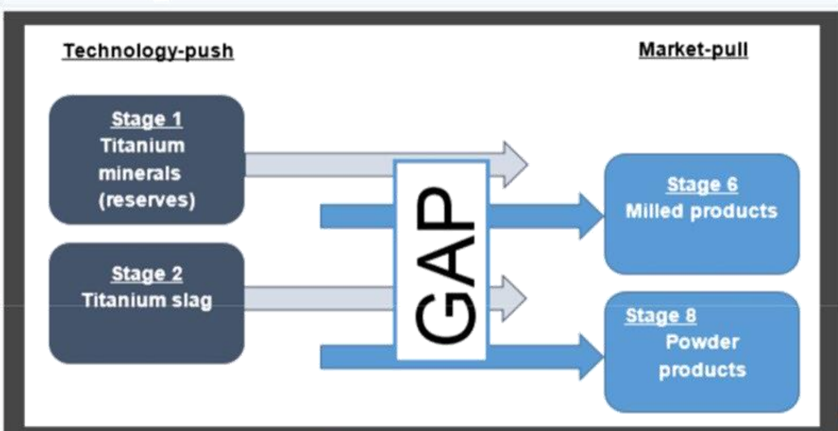
The biggest titanium milled product industries are aerospace and chemical and the biggest industries for titanium powder are aerospace and automotive (QY Research Group, 2017; Hohne-Sparborth, 2018).

INDUSTRY	WHY PREFERRED METAL (TOP 2)	EXAMPLE OF PRODUCT
AEROSPACE PRODUCTS	High strength to weight ratio High heat transfer	Airframes and engines parts
MILITARY & SPACEFLIGHT	High strength to weight ratio High heat transfer	Missiles, armour, spacecraft outer fuel tanks sheeting and spacecraft wings
CHEMICAL	Excellent resistance to chemical corrosion High heat transfer	Cooling pipes, pumps, valves & heat exchangers
POWER	Excellent resistance to chemical corrosion High heat transfer	Heat exchangers, pipes and pumps
SHIPBUILDING	Excellent resistance to sea water corrosion High heat transfer	Propellers, propeller shafts, sheets, sonic depth gauge, deck
OIL AND GAS	Resistance to chemical & sea water corrosion High specific strength of titanium alloys	Pipes, pumps, valves and plumbing fixtures
METALLURGY	Excellent resistance to chemical corrosion High melting point	Electrorefining, titanium alloys (rods, plates and pins)
DESALINATION	Excellent resistance to sea water corrosion High strength to weight ratio	Titanium tubes and heat exchanger plates
CONSTRUCTION	Corrosion resistance to sea water Low coefficient of thermal expansion	Faced material, titanium cladding and titanium panels (Aesthetics)
AUTOMOTIVE	High strength to weight ratio Low Young's modulus (low deformation)	Valves, springs, retainers, connecting rods, exhausts and under panels
CONSUMER & MEDICAL	Biocompatible Low Young's modulus (low deformation)	Hip joints, dental implants, tennis rackets, golf clubs and bicycle frames

3. Roadmapping

Based on South Africa's current titanium industry the proposed roadmapping approach for this research is a prospective technology-push/market-pull approach. Prospective because the South African titanium industry is looking from its current position and considering what is required for future direction. Out of the four stages of the titanium metal value chain, present in South Africa, two stages fall within the upstream and two within the downstream processing of titanium metal. The upstream stages will initiate the technology-push and the downstream stages the market-pull. The missing stages in the middle can be defined as the titanium industry gap.

- **Technology-push:** Start with existing research and create roadmap by identifying diverse possibilities the research could lead to
- **Market-pull:** Start at the desired end product and identify the required research and development required to arrive at desired end product



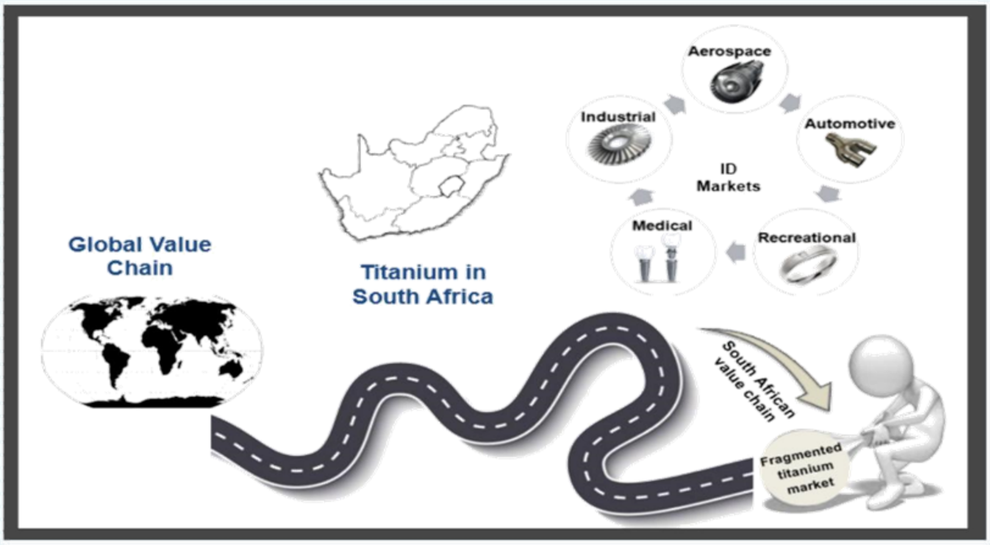
For more information contact Nicolene at: nroux@csir.co.za

powered by PIKTOCHART

#3 INFORMATION SHEET

4. The way forward

- The data to be collected from the interviews will be compiled and used to generate a South African titanium industry vision for medium term (5 years) to long term (10 years).
- The vision does not have to be limited to achieving a complete titanium metal value chain, but could also be for the development of a fragmented titanium metal value chain.
- A fragmented titanium metal value chain could be developed by strengthening the stages that the country is already involved in by:
  o remaining the largest producer of titanium minerals,
  o improving beneficiation techniques,
  o improving titanium machining capacities and specialising in certain finished products, and/or by
  o improving additive manufacturing and other titanium powder metallurgy manufacturing techniques.
- South Africa could reduce its fragmentation by systematically growing on the titanium value chain over time by:
  o producing $TiCl_4$ locally and growing the TiO_2 (pigment industry),
  o purchasing electrodes or ingots and producing powder locally through spheroidisation,
  o buying in larger quantities of titanium powder to feeding the growing powder metallurgy market, and/or by
  o build a Kroll plant.
- Another point to consider is the potential to develop less stringent titanium markets (based on quality). In this scenario finished products could be produced for the chemical industry instead of for the aerospace industry while developing skills and competencies.



Reference list:

- Hohne-Sparborth, T. (2018) 'Socio-economic impact of metal industries', in *Titanium USA 2018*. Las Vegas, NV.
- QY Research Group (2017) 'Global Titanium Powder Market Research Report 2017'. Available at: http://www.reportsnreports.com/reports/800353-global-titanium-powder-market-research-report-2017.html.
- Roberts, J. (2018) 'Titanium metal- what will the next decade bring?', in *Titanium USA 2018*. Las Vagas: Roskill.
- Roux, R. N., Van der Lingen, E. and Botha, A. P. (2019) 'A SYSTEMATIC LITERATURE REVIEW ON THE TITANIUM METAL PRODUCT VALUE CHAIN', in *SAIIEneXXXt Proceedings*. Port Elizabeth.

For more information contact Nicolene at: nroux@csir.co.za

15.2. Appendix B. The Interview Template

A roadmap for the titanium industry in South Africa (Interviews)

Name	
Sector	
Company	
Stage	
Date	

Question 1

"What is the current position of your stage of the value chain and what development and improvements do you expect in the future"

Are you still involved in the titanium industry: YES / NO

a) Where are you now? *Where was the industry when you left?*

b) Where do you want to go? What was your vision for the titanium industry?

Question 2

"Who is/was your supplier and who is/was your market?"

Local or international? Is the market saturated?

Supplier:

Market:

-

Question 3

"What do you consider the preferred market/industry is for South Africa within the titanium metal industry?"

1) 2) 3)

Question 4

"Based on your knowledge of the South African titanium metal industry, should we keep doing what we are doing (part of fragmented value chain), or should we try to develop the complete titanium metal value chain?"

Fragmented value chain	Complete value chain
Which stages and why?	

Question 5

"Why is it important for you that South Africa follows the value chain route you suggested? "

- Socio-economic reasons
- Patriotism
- Profit
- Government
- Too ambitious

Question 6

"Market-pull or technology-push-approach? Or both?"

How would you have approached this?

Question 7

Where do you see the major developments within the South African titanium metal industry within the next three years?

Next 3 Years		
Minerals and Ore	Stage 1&2	
$TiCl_4$	Stage 3	
Sponge	Stage 4	
Melted Products	Stage 5	
Mill Products	Stage 6	
Powder production	Stage 7	
Powder Products	Stage 8	

Question 8

"Where do you see the major developments within the South African titanium metal industry within the next 10 years?"

Next 10 Years		
Minerals and Ore	Stage 1&2	
$TiCl_4$	Stage 3	
Sponge	Stage 4	
Ingots*	Stage 5	
Mill Products	Stage 6	
Powder production	Stage 7	
Powder Products	Stage 8	

Question 9

"What stage of the titanium metal value chain do you feel has the most market disruption potential?"

15.3. Appendix C: Interview Question Guide

Interview questions guide
(Layout of the structure)

Before the interview the interviewee received an information sheet (Appendix A: Interviewee Information Flyer) with relevant information to prepare for the interview. The interviews were designed to take no more than 20 minutes but on average the conversation continued for approximately 60 minutes.

The interviews followed a semi-structured approach, meaning that additional questions could be added if the conversation permitted it. In the same manner irrelevant themes were excluded or added from the conversation if needed.

A. The interview started with a brief introduction of the interviewer followed by her background and the background of her research.
B. A short discussion was held on the interviewee's understanding on the information received prior to the interview.
C. The interviewer then proceeded to explain/discuss the titanium product value chain:
   - The global value chain
   - Where South Africa fits into the value chain
   - Beneficiation was be discussed
   - Fragmentation within the titanium value chain was discussed
   - Specific reference was made to the relevant stage of the value chain the interviewee was involved in

Appendix B. The Interview Template was the hard copy that was printed out and completed during each interview and remained specific to each interviewee. Appendix C: Interview Question Guide, was only viewed by the interviewer and used as a guide. The same questions are presented in both appendices.

QUESTIONS FOCUSING ON INTERVIEWEE'S REFERENCE FRAMEWORK

1. **"What is the current position of your stage of the value chain and what development and improvements do you expect in the future"**
   - "Where are you now and where do you want to go?"

- Are there any innovations or technological advances you are working on?

2. **"Who is your supplier and who is your market?"**
    - Is it local or international?
    - Are you the sole supplier?
    - Is the market saturated or are you struggling to keep up?

QUESTIONS FOCUSING ON THE SOUTH AFRICAN TITANIUM INDUSTRY

3. **"What do you consider the preferred marked is for South Africa within the titanium metal industry?"**
    - The question was accompanied by a list of potential markets (also discussed on information sent prior to interview), as well as a short description of each.
    - The description included the size of the market globally

4. **"Based on your knowledge of the South African titanium metal industry, should we keep doing what we are doing (part of fragmented value chain), or should we try to develop the complete titanium metal value chain?"**
    - This was a discussion where alternative options were discussed (also discussed on information sent prior to interview) e.g.:
        - Buy in electrodes or wire to produce spherical titanium powder
        - Just buy in powder
        - Only produce $TiCl_4$ for the pigment industry

5. **"Why is it important for you that South Africa follows the value chain route you suggested? "**
    - OR SIMPLY
    - "Why do you suggest/prefer this route?"
        - Full value chain
            - Socio-economic reasons → job creation
            - Patriotism → It is our minerals, we should profit from them
            - Because this is what the government wants
            - Profit
        - Fragmented value chain
            - The establishment of the value chain is too difficult

- We are several years away from even considering a complete value chain
- would be cheaper and faster to remain fragmented

6. **"Market-pull or technology-push approach? Or both?"**
    - Indicate which one makes the most sense and motivate why.

7. **"Where do you see the major developments within the South African titanium metal industry within the next three years?"**
    - This is seen as medium-term in roadmapping

8. **"Where do you see the major developments within the South African titanium metal industry within the next 10 years?"**
    - Stage 1 & 2 → Ti minerals and slag
    - Stage 3 → $TiCl_4$
    - Stage 4 → Sponge
    - Stage 5 → Ingots
    - Stage 6 → Mill Products
    - Stage 7 → Metal powder
    - Stage 8 → Powder products

15.4. Appendix D: The Survey Design

A Roadmap for the South African titanium metal industry

Thank you for participating in the interviews for Nicolene Roux's research on "A roadmap for the South African titanium metal industry". You are now invited to participate in the followup survey.

If you are receiving this survey, you have been identified as an expert in your related stage of the value chain. The aim of this survey is to confirm and conclude the vision for the local titanium metal industry (as identified by 37 interviewees) and to fill any additional gaps and uncertainties around the value chain.

1* Permission

By clicking continue you agree that: " I, hereby voluntarily grant my permission for participation in the project as explained to me by Nicolene Roux. The nature, objective, possible safety and health implications have been explained to me and I understand them. I understand my right to choose whether to participate in the project and that the information furnished will be handled confidentially. I am aware that the results of the investigation may be used for the purposes of publication".

☐ Continue

Section 1- The vision for each of the eight value chain stages

During the interview, Nicolene introduced to you, the eight-stage titanium metal value chain used for her study.

A graphic representation of these stages were displayed in the email invitation.

2* What stage(s) of the titanium metal value chain do you feel comfortable commenting on? Feel free to select more than one. You will still be able to comment on all of the value chain stages. N/A = Not applicable.

- ☐ Stage 1 and 2: Ti mineral reserves and slag production
- ☐ Stage 3: TiCl4 production
- ☐ Stage 4: Ti Sponge production
- ☐ Stage 5: Melted products
- ☐ Stage 6: Mill products
- ☐ Stage 7: Ti metal powder
- ☐ Stage 8: Powder products

3* The 10 year vision for stage 1 and 2 (mining and upgrading) of the titanium metal value chain is to sustainably mine and upgrade titanium mineral concentrates (increased mining in next three years but level out in 10 years), while implementing more efficient technologies.

Do you agree with this vision?

Please specify your answer!

- ☐ Agree
- ☐ Disagree
- ☐ N/A
- ☐ Comments

4* The 10 year vision for stage 3 ($TiCl_4$ production) of the titanium metal value chain is to have access to chlorination technology (through an industrial partner) by 2030 and have acquired a big enough market for pigment and metal production (local and Africa) for this plant to be economically feasible.

Do you agree with this vision?

Please specify your answer!

- ☐ Agree
- ☐ Disagree
- ☐ N/A
- ☐ Comments

5* There is no vision for Stage 4 (Ti-sponge production) of the titanium metal value chain. South Africa should not build a titanium sponge plant in the next decade.

Do you agree with this vision?

Please specify your answer!

☐ Agree ☐ Disagree ☐ N/A

☐ Comments

6* There is no vision for Stage 5 (melted product production) of the titanium metal value chain as South Africa should not build a melting facility in the next decade.

Do you agree with this vision?

Please specify your answer!

☐ Agree ☐ Disagree ☐ N/A

☐ Comments

7* The 10 year vision for Stage 6 (mill product production) of the titanium metal value chain is to expand on the local capability to produce final and intermediate mill products for both the local and the international markets with the focus on aerospace, medical and the chemical industries.

Do you agree with this vision?

Please specify your answer!

☐ Agree ☐ Disagree ☐ N/A

☐ Comments

8* The 10 year vision for Stage 7 (Ti powder production) of the titanium metal value chain is to be able to satisfy the local titanium metal powder demand and to become global suppliers of high quality titanium metal powders, either through novel local technology or imported technology.

Do you agree with this vision?

Please specify your answer!

☐ Agree ☐ Disagree ☐ N/A

☐ Comments

9* The 10 year vision for Stage 8 (Ti powder products) of the titanium metal value chain is to grow production capacity and expertise with the aim to become world leaders in specialised/niche part production with the focus on the aerospace, medical and consumer industries.

Do you agree with this vision?

Please specify your answer!

☐ Agree ☐ Disagree ☐ N/A

☐ Comments

Section 2- Roadmapping 3 Years

Based on the visions obtained from 37 expert interviews, South Africa should not have a complete titanium metal value chain but remain fragmented for the next decade. Although a fragmented value chain has been identified for the South African titanium metal industry, interviewees expect that this fragmentation will decrease towards 2030. This section will highlight the reasons identified by the interviewees for fragmentation. Please comment on whether you agree or disagree with the fragmentation and the reasons supplied.

The 3-year roadmap:

The envisioned 3-year titanium metal value chain has been identified to look the same as the 2020 value chain with only four active stages. These stages are: stage 1 (titanium mineral reserves), stage 2 (titanium slag), stage 6 (mill products) and stage 8 (powder products).

Please refer back to the invitation email for the graphic display of the value chain.

10 The key elements identified for EXCLUDING $TiCl_4$ from the three year local titanium metal value chain are presented in the boxes below.

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- [ ] Without government level agreements with industrial/international partners, South Africa has no access to chlorination technology
- [ ] South Africa will not be able to compete with existing TiCl4 markets (e.g. China already dominates the African market)
- [ ] TiCl4 production is driven by the pigment market. For a TiCl4 plant to be profitable along the economic cycle the plant needs to produce 100 000t of TiCl4 per year. South Africa does not have a big enough pigment or titanium metal market to sustain such a plant

Comments

11 The key elements identified for EXCLUDING titanium sponge from the local titanium metal value chain are presented in the boxes below (this is for both the three year and the ten year roadmaps).

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- [ ] It is not economically viable to construct a titanium sponge production plant locally as South Africa would not be able to compete with the international market.
- [ ] South Africa is experiencing an electricity-supply crisis resulting in electricity constraints.
- [ ] The investment risks are too high for industrial partners.
- [ ] Sponge production is environmentally unfriendly.
- [ ] The titanium sponge market is over-saturated.

Comments

12 The key elements identified for EXCLUDING titanium melted products from the local titanium metal value chain are presented in the boxes below (this is for both the three year and the ten year roadmaps).

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- ☐ South Africa is experiencing an electricity-supply crisis resulting in electricity constraints.
- ☐ The country is not producing sponge to melt.
- ☐ This facility would be too capital intensive.
- ☐ South Africa is too far from the market to compete internationally.
- ☐ South Africa does not have the required skills or experience with the technology.
- ☐ It would be cheaper to import ingots to produce a spherical titanium metal powder than to produce the ingots locally.

Comments

13 The key elements identified for EXCLUDING titanium metal powder production from the three year local titanium metal value chain are presented in the boxes below.

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- ☐ Research is progressing too slow (scaling down instead of scaling up).
- ☐ The process is complex and is still in a development stage.
- ☐ South Africa should not compete in the global race to create a cheaper titanium production process as there are too many countries attempting this all much better fu
- ☐ South Africa does not have the required resources such as skills and funding.
- ☐ The unreliable South African electricity supply is generating economic instability and costing companies' money. Powder production technology is electricity intensive.

Comments

14* Do you agree with the three year titanium metal value chain?

- ☐ Agree
- ☐ Disagree
- ☐

Comments

Section 3- Roadmapping 10 Years

Ten-year roadmap

The fragmented nature of South Africa's 10-year value chain has been identified to be more complete whilst only missing the sponge and melted product sections. The reasons for these two sections not being developed in the next 10 years remain the same as the three year period. The reasons for adding stage 3 ($TiCl_4$) and stage 7 (titanium metal powder) for the 10-year vision will now be discussed.

The South African fragmented titanium metal value chain is envisioned to have the following stages:

Stage 1 (Titanium mineral reserves)

Stage 2 (Titanium slag)

*Stage 3 ($TiCl_4$ production) - Added from 10-year vision

Stage 6 (Mill products)

*Stage 7 (Titanium powder production) - Added from 10-year vision

Stage 8 (Titanium powder products)

Stage 4 (titanium sponge production) and stage 5 (melted product production) are expected to be absent or still being developed by 2030.

15 The key elements for INCLUDING $TiCl_4$ to the ten year local titanium metal value chain are presented in the boxes below.

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- [ ] The successful development of a local primary powder production process would create a market for a small novel TiCl4 plant specifically for local powder production.
- [ ] Technology for a 100 000t plant is to be sourced internationally.
- [ ] Market growth within the pigment industry creating a local demand in TiCl4 production.
- [ ] The advancement of local TiCl4 chlorination research to commercial scale (novel or old technology).

Comments

16 The key elements for INCLUDING titanium metal powder production to the ten year local titanium metal value chain are presented in the boxes below.

Please tick the boxes you agree with and provide comments or additional points to consider in the block below

- [ ] A breakthrough within local research, a semi-commercial ±500t /a titanium metal powder plant (novel or old technology).
- [ ] With the aid of government or a multinational expansion, a committed industrial partner should be obtained to bring in existing titanium metal powder technology (direct electrothermal).
- [ ] Produce commercially pure (CP) and/or titanium alloy powders from imported electrodes via spheroidisation or atomisation.
- [ ] Applying the hydrogenation-dehydrogenation (HDH) powder production method on imported sponge to produce angular powder.

Comments

17* Do you agree with the ten year titanium metal value chain?

- [ ] Agree
- [ ] Disagree

18 Do you have any other comments?

19 This is an anonymous survey, but if you want to disclose your identity to Nicolene, please do so in the block below.