Framework for effective Additive Manufacturing education at South African universities

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Abstract

Additive Manufacturing (AM) which is also known as 3D printing technology; is a process by which digital 3-dimensional data is used to build up components or parts layer upon layer by depositing material. Additive manufacturing has been identified as a 21st century emerging technology and is becoming popular within the academia and several industries globally. At present, Additive manufacturing has a wide variety of potential application areas such as automotive, aerospace, healthcare, electronics, manufacturing, education, tooling, food, construction, etc. In this era of Fourth Industrial Revolution, FIR, also known as 'Industry 4.0', additive manufacturing has been recognised as one of the nine technologies of industry 4.0 (i.e. Internet of Things, Big Data and Analytics, Cybersecurity, Cloud Computing, Simulation, Augmented Reality, Autonomous Robots, Additive Manufacturing and Horizontal and Vertical System Integration) that is expected to revolutionize different sectors and bring about a significant transformation in industrial production and manufacturing industries.

South Africa is one of the active countries on the African continent promoting additive manufacturing technology, education and research both in the academia and industry. The South African government through the Department of Science and Technology has invested significantly towards research activities and growth of AM technology. As additive manufacturing technology is growing in South Africa, there is a need for more educated personnel and industry professionals in the field. In 2013, during a stakeholder workshops in South Africa, education was highlighted as one of the main priorities to ensure a successful adoption of AM technology in South Africa. The stakeholders include people from industry, government, higher education institutions, 3D printing service providers and R&D institutes.

Additive manufacturing technologies are still at an infant stage and to reap the full potential of this technology, its inclusion in the educational curriculum is crucial. To achieve this, an effective framework for additive manufacturing education must be developed. Through a comprehensive literature survey, it was identified that there is no specific framework for additive manufacturing education at the universities worldwide; including South African universities as well. As part of South African Additive Manufacturing Strategy which is to ensure AM education at different educational levels; the development of a short, medium and long-term educational framework for AM was identified as one of the essential measures to achieve this.

The research problem for this study is that "as several manufacturing and industrial sectors are adopting AM technologies in South Africa, there is a need for more university graduates, most especially in science and engineering with fundamental or in-depth knowledge of AM technology to

work with the emerging AM sectors or 3D printing service bureau in South Africa. It is very important to develop an effective framework for AM education for South African universities that will further promote AM education among students, academia and industry's professionals".

Therefore, this study focuses on "Additive Manufacturing Education" and aimed to investigate the impacts of AM technology at selected South African universities and thereafter, to propose a framework for effective additive manufacturing education using South African universities as the case study. The South African universities were selected because of the active presence of AM research group, AM/3D printing lab and well-equipped state-of-the-art AM in-house facilities for use of the students and academics. This study is expected to answer one main research question and four sub-research questions as rightly formulated and stated in the first chapter of the thesis.

This study has been conducted using a case study research approach with the main data collected through a comprehensive structured questionnaire and followed by open-ended questions distributed among university students and academics. The questionnaire was carefully designed based on literature reviews. The factors/variables used were identified through a literature survey and were considered suitable in the development of a framework for additive manufacturing education and these factors includes - additive manufacturing technology, technology transfer, educational curriculum, in-house facilities and research and development (R&D). The first phase involved a pilot survey circulated among academics, AM experts and 3D printing service bureaus with the aim to complete the questionnaire and to provide significant feedback as relating to the closed-ended and open-ended questions in the questionnaire, hence, it assisted the researcher to improve the quality of the measuring instrument. The second phase involved the main data collection; and the questionnaires were circulated among students and academics across selected South African universities and appropriate hypotheses were also formulated. The third phase involved the statistical analysis, discussion and interpretation of the data. Finally, the framework for AM education was developed.

The main contribution of this study towards the existing body of knowledge in additive manufacturing technology was in the form of a proposed framework for additive manufacturing education at the universities. The framework explains the main activities or factors that would ensure a successful AM education framework/implementation at the universities. The proposed framework would allow the government sectors/department/bodies and key players in AM in South Africa and abroad to see the need to invest significant towards the advancement of AM technology, education and research activities at the universities.

Declaration

I hereby declare that this thesis being submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Development and Management Engineering at the Potchefstroom Campus of the North-West University is my work and has been properly language edited in accordance with the requirements of the university and the declaration of the language editing can be found in Appendix G as provided by the language editor (Prof. Annette Combrink).

The research has not been submitted before for any degree or examination in any other universities in South Africa and abroad. I understand and accept that the copies that are submitted for examination become the property of the North-West University.

Micheal O. Alabi
November 2018.

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Publications

The following papers as titled were recently submitted for publication in an international journal during the course of this study.

1. Micheal O Alabi*, Deon de Beer and Harry Wichers – Authors

   Applications of Additive Manufacturing at Selected South African Universities: Promoting Additive Manufacturing Education –

   Accepted for Publication in Rapid Prototype Journal on 22nd February 2019.

   The full article can be found in **Appendix F.**

2. Micheal O Alabi*, Deon de Beer and Harry Wichers – Authors

   Entry-Level FDM 3D Printers as a Tool for Additive Manufacturing Education using Idea 2 Product (I2P) ® Lab Concept –

   Re-Submitted to Rapid Prototyping Journal in February 2019 and Awaiting the Journal editorial decision.

   The full article page can be found in **Appendix G**.

3. Micheal O Alabi*, Deon de Beer, Harry Wichers and Cornelius P. Klopper – Authors

   Framework for Effective Additive Manufacturing Education: A Case Study of South African Universities.

   Newly Submitted to Rapid Prototyping Journal on 22nd February 2019 and Awaiting the Journal Editorial decision.

   The first page of the article can be found **Appendix H**

Key Words

Additive Manufacturing, South African Universities, Industrial Sectors, Rapid Prototyping, Traditional Manufacturing, Conventional Manufacturing, Substantive Manufacturing, Technology Transfer, Sustainability, 3D Printing Technology, Entry-level FDM 3D Printers, High-end Industrial Additive Manufacturing Machines, Industry 4.0. Educational Curriculum.

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List of Acronyms

3DP:	Three-Dimensional Printing
ABS:	Acrylonitrile Butadiene Styrene
A&D	Aerospace and Defence
AM:	Additive Manufacturing
AME:	Additive Manufacturing Education
AMCoC:	Additive Manufacturing Centre of Competence
ASTM:	American Society for Testing and Materials
AMT:	Advanced Manufacturing Technologies
CAD:	Computer-Aided Design
CAE:	Computer Aided Engineering
CI:	Confident Interval
CAP:	Computer-Aided Production
CPAM:	Collaborative Programme for Additive Manufacturing
CSIR:	Council for Scientific and Industrial Research
CT:	Computerized Tomography
CUT:	Central University of Technology
DLP:	Digital Light Processing
EBM:	Electron Beam Melting
DMLS:	Direct Metal Laser Sintering
FDM:	Fused Deposition Modeling
FIR:	Fourth Industrial Revolution
GE:	General Electric
HEI:	Higher Education Institutions
I2P:	Idea 2 Product
ISO/TC:	International Organization for Standardization/Technical Committees
KMO:	Kaiser-Meier-Olkin
LCA:	Life-Cycle Analysis
LOM:	Laminated Object Manufacturing
LMD:	Laser Metal Deposition
MC:	Mass Customization
MRI:	Magnetic Resonance Imaging
MSc:	Master of Science
MJM:	Multi-Jet Modelling
NLC:	National Laser Centre
NRF:	National Research Foundation
NSF:	National Science Foundation
NSTF:	National Science and Technology Forum
NWU:	North-West University
PBL:	Problem-Based Learning
PC:	Personal Computer
PC:	Polycarbonate
PLA:	PolyLactic Acid
PBIH:	Powder Bed and Inkjet Head
P3DP:	Plaster-Based 3D Printing
R&D:	Research and Development

RAPDASA:	The Rapid Product Development Association of South Africa
RM:	Rapid Manufacturing
RP:	Rapid Prototyping
SA:	South Africa
SCM:	Supply Chain Management
SET:	Science. Engineering, Technology
SGC:	Solid Ground Curing
SLA:	StereoLithography Apparatus
SLS:	Selective Laser Sintering
SHS:	Selective Heat Sintering
S/N:	Serial Number
STEM:	Science, Technology, Engineering and Mathematics
SU:	Stellenbosch University
UC:	Ultrasonic Consolidation
TOT:	Transfer of Technology
UJ:	University of Johannesburg
US:	United States
VUT:	Vaal University of Technology

Chapter 1

1. Introduction

This chapter presents the research background for the study, problem statement, research aim, objectives, research questions and the scope of the research. The research design/methodology is described diagrammatically. The significance of the research and overview of the research layout are described briefly, and the chapter ends with summary.

1.1 Introduction to the study

According to Wohlers (2010) AM is the official industry standard term (ASTM F2792) for all applications of the technology. It is defined "as the process of joining materials to make objects from 3D model data, and it is usually layer upon layer, as opposed to subtractive manufacturing methodologies". AM processes were first demonstrated more than 25 years ago. AM is also known as rapid prototyping, additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication (Wohlers, 2010).

Wohlers' (2011) report stated that "3D printing technology is having an impact on product development and manufacturing around the world and most especially among companies such as Airbus, Audi, BMW, Boeing, Cochlear, Ford, General Electric, Hewlett-Packard, Nike, ResMed, and Sunbeam as well as numerous small and medium-sized organizations which are using the technology extensively". Most of the parts produced by additive manufacturing are going into aircraft, race cars, home and office products, and human beings as implant and prostheses (Wohlers, 2011). Some of the characteristics of AM are: reduction in waste material, lower labour costs, speeds in development and testing phase, and product customisation and production of complex metal parts (CSIRO, 2015). Another significant benefit of AM is that it helps to reduce mistakes and delays to a minimum and produce winning products (Wohlers, 2011).

It is predicted that AM technology would play a significant and game-changing role in the Fourth Industrial Revolution, FIR, also known as 'Industry 4.0'. As recorded, AM technology has been active in South Africa for the past 26 years and it promises to play an ever-growing role in efforts to re-industrialise the economy of South Africa (NSTF, 2016). During the National Science and Technology Forum (NSTF) in March 2016, a discussion forum for Science, Engineering, Technology for Socio-Economic Growth in South Africa; the panel discussions focused on Additive Manufacturing applications in South Africa and as part of the discussion, it was stated that the AM sector of South Africa is being led by higher learning institutions and science councils, and the leading institutions in this regard are Central University of Technology (CUT) and Vaal University of Technology (VUT) where products are being made on a daily basis for various sectors. CUT focuses primarily on serving the medical industry while VUT services the tooling and casting industries". North-West University (NWU) and Stellenbosch University (SU) are also key players AM among the South African universities (NSTF, 2016). Later in this chapter, an extensive discussion on AM education, research activities and in-house facilities at the CUT, VUT, SU, NWU and University of Johannesburg will be discussed. During the panel discussions, it was noted that industry-led research is essential for additive manufacturing to succeed in South Africa (NSTF, 2016).

The Rapid Product Development Association of South Africa (RAPDASA) is the representative body of the technical service providers and researchers in the product development of AM field in South Africa (Du Preez and De Beer, 2006). RAPDASA reported that approximately 94% of all AM machines sold in South Africa are in the entry-level 3D printers' category. A survey was carried out in 2010 and worthwhile analysis was made on the data, and it shows that industry ownership of AM machines now overtakes university and science institution ownership by far. As stated by RAPDASA, in 2010, only approximately 2 or 3 of universities in South Africa have AM equipment in-house, whilst 25% of these universities pursue AM as a research field.

Additive manufacturing technology market in South Africa (SA) has grown from a single 3D systems StereoLithography Apparatus 250 (i.e. SLA 250) in 1991 (Wohlers, 2010), to approximately 3500 machines in 2015 as shown Figure 1.1. It is obvious that the AM landscape and sales in South Africa have experienced a tremendous growth within the past eight years (2008 to 2015). At the end of 2006, it was recorded that approximately 90 AM/3D printing machines were available in SA. In December 2015, a reasonable number of 3500 AM machines in South Africa are in the high-end of market (i.e. 3D printing service bureau), science councils and higher institutions (De Beer, 2009; De Beer, 2015). This shows that the future of AM in SA is very bright when compared to other African countries. Section 3.3 of Chapter 3 provides an extensive history of earlier adoption of AM technology in SA. Apart from the growth seen in South Africa AM market, also from a global perspective, AM market has experienced a significant development and growth over the past 20 years in term of products and services and this is very evident across different industrial sectors. The next sub-section (1.1.1) presents the various industrial applications of AM technology as relating to different sectors.

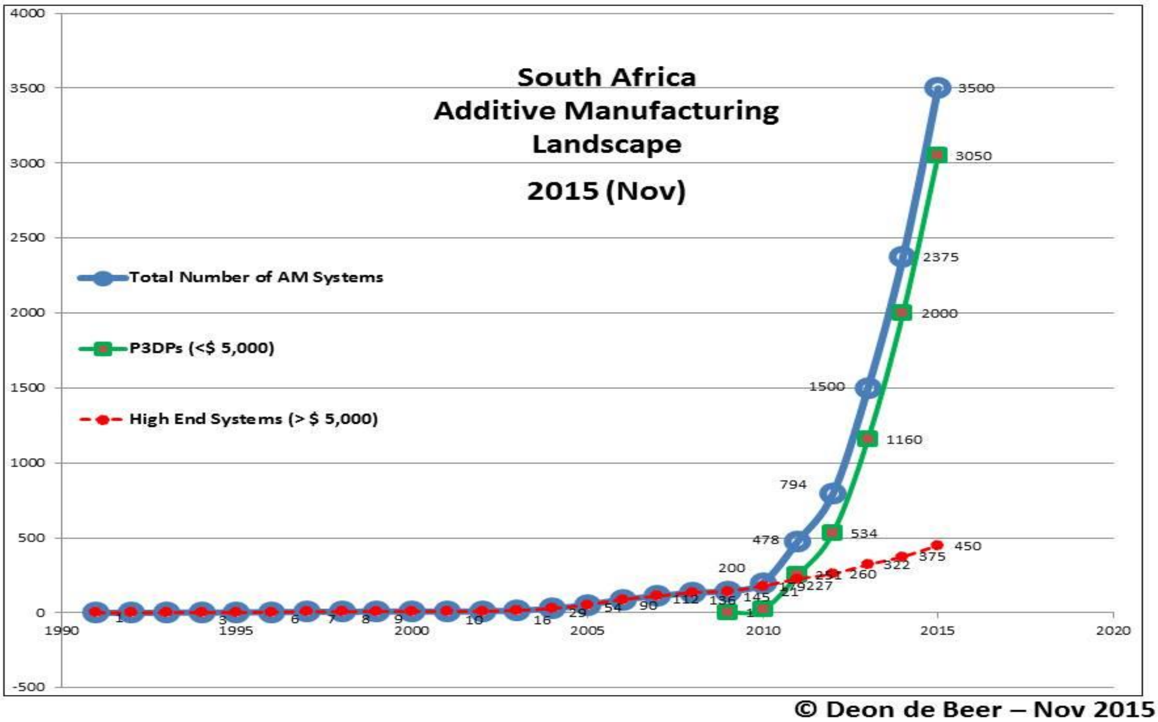


Figure 1. 1: South African Additive Manufacturing Landscape/Growth of 3D Printers in SA, 1991-2015

Source: Supplied by Prof Deon De Beer in 2015

1.1.1 Applications of Additive Manufacturing from different industries

According to Mpofu *et al.* (2014) AM has been found to be useful in sectors such as manufacturing, industrial design, jewellery, footwear, architecture, engineering and construction, automotive, aerospace, dental and medical industries, education, geographic information systems, civil engineering, and many other areas. The 2015 Gartner's report on AM/3D printing technology shows that the rapid prototyping market is expected to exceed $20.2 billion in the year 2020 (Wohlers, 2012). More so, Gartner's 2017 report reviews the tremendous increase in the application of AM technologies as shown in Figure 1.2.

The Gartner hype cycle in Figure 1.2 identifies five stages of AM trends as follows: *the innovative trigger*, *inflated expectation of peak*, *trough of disillusionment*, *enlightenment slope*, *and the plateaus of productivity* (David, 2017; Goehrke, 2019).

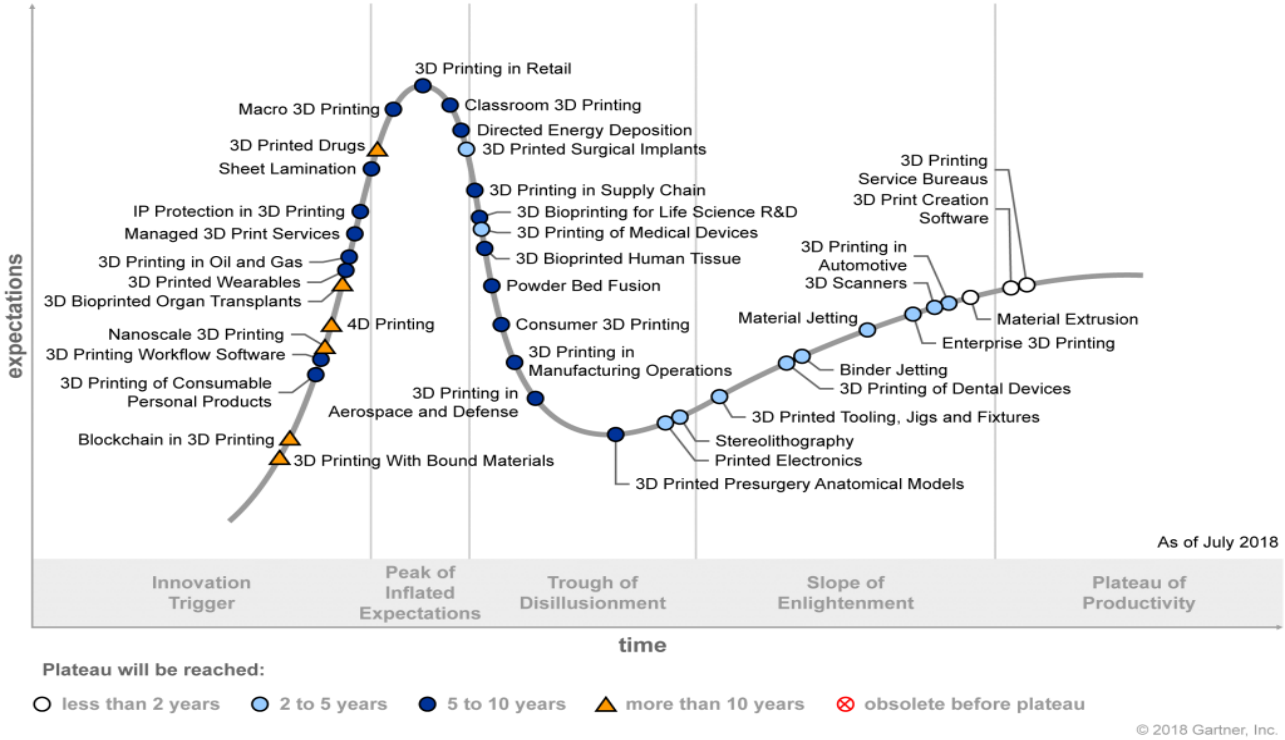


Figure 1. 2: Advancement in Additive Manufacturing Technologies Based on Gartner Report in 2017.

Source: Goehrke (2019).

As shown in Figure 1.2, most of the AM application areas are still at the embryonic stage in term of growth and development. The report explains that "The hype around consumer printers is dying out but will soon be replaced with hype around 3D printed critical components in commercial airliners; fully-printed rocket engines; 3D printing in schools and universities; animal-rights-friendly bio-printed human tissues for drug toxicity and cosmetics testing; and, ultimately, 3D printed electrics and electronics starting with the replacement of wiring with functional 3D printed enclosures containing embedded conductive pathways" (IDTechEx, 2014).

1.1.2 Forecast on Worldwide Additive Manufacturing/3D Printing Industry

In 2014, Wohler's report provides the forecast on worldwide 3D printing industry as shown in Figure 1.3.

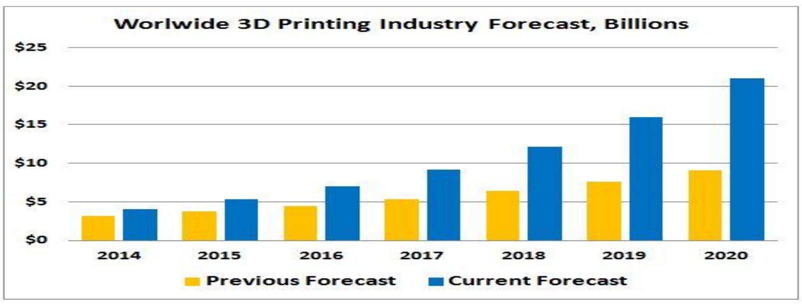


Figure 1. 3: Wohlers Report 2014, Forecast on Worldwide 3D Printing Industry
Source: Wohlers Associates, Author's Calculations (2014)

Furthermore, the global AM industry is expected to grow from $3.07 billion in revenue in 2013 to $12.8 billion by year 2018, and to exceed $21 billion in worldwide revenue by 2020 as seen in Figure 1.3. Wohlers (2013) reports that the AM industry would grow to become a $10.8 billion industry by 2021. Based on the forecast of Wohlers report in 2014 on worldwide 3D printing industry as presented in Figure 1.3, it would be a good reason for SA's additive manufacturing body (RAPDASA) to accelerate their efforts to get AM into the local manufacturing industry in the country and to expand and increase their research productivity in AM at the universities and R&D institutes; so as to compete with other world-class AM institutes and centres of excellence in AM globally; and in return help to boost the SA economy.

1.1.3 Additive Manufacturing Research Activities and In-House Facilities at Selected South African Universities

As part of the strategy to promote AM technology, education and research activities in South Africa, Du Preez and De Beer (2015) present the South African AM technology roadmap which includes different focus areas for future interventions in the field of AM as shown in Figure 1.4.

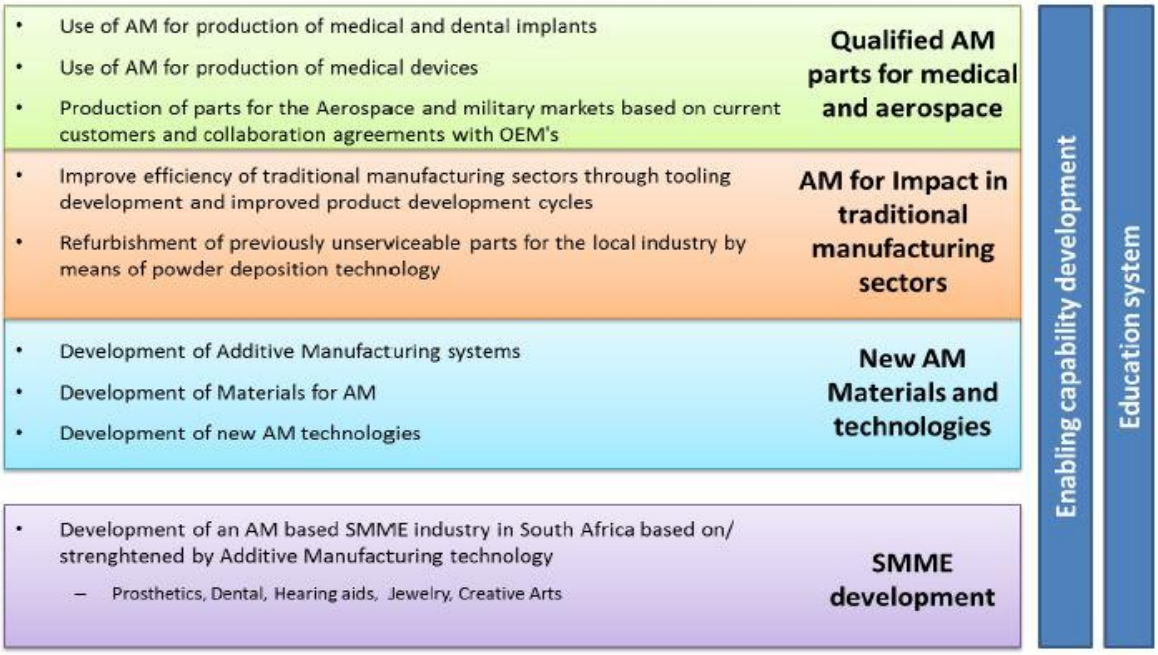


Figure 1. 4: Recommendations of the South African AM Technology Roadmap
Source: Du Preez and De Beer (2015)

The South African AM technology roadmap was designed with an intention to guide AM players in the country in identifying economic opportunities, addressing technology gaps, focusing on development programmes, informing investment decisions and to enable local SAs' companies and industry sectors to become global leaders in selected areas of AM (Du Preez and De Beer, 2015).

More so, Du Preez and De Beer (2015) developed a commercialised AM technology platform for SA's industries as presented in Figure 1.5. Through this platform, the concept of a national Additive Manufacturing Centre of Competence (AMCoC) framework was introduced which primarily serves as the implementation vehicle for SA AM Roadmap.

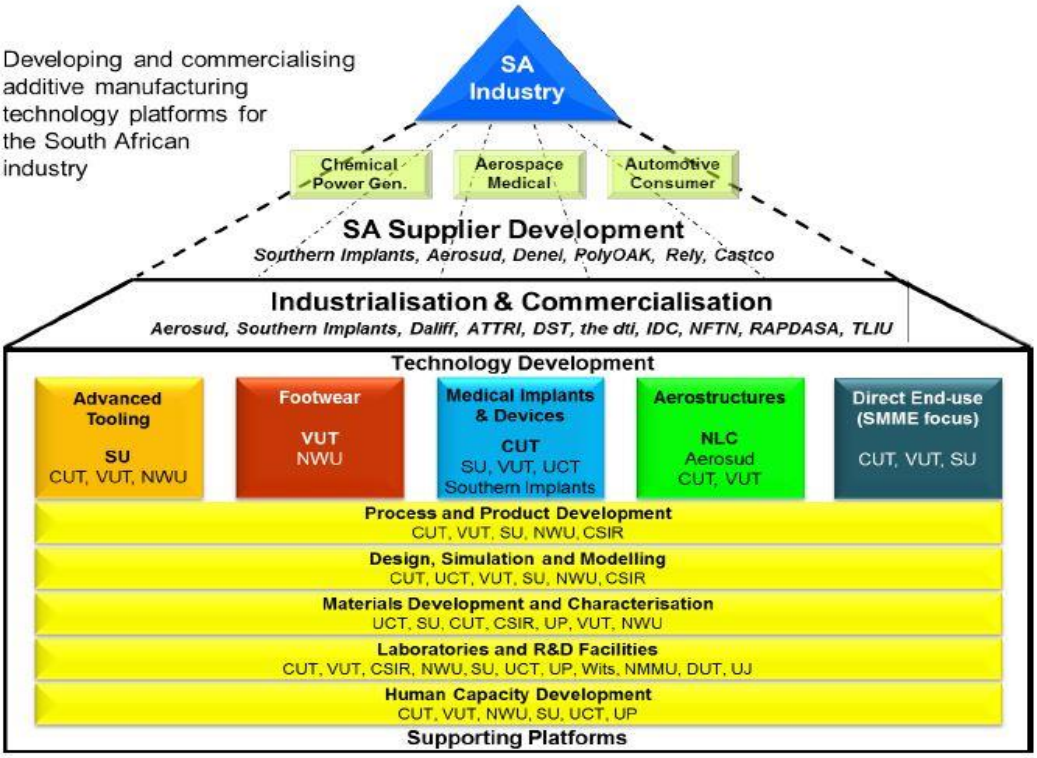


Figure 1. 5: Activities and Collaborators of the South African Additive Manufacturing Centre of Competence
Source: Du Preez and De Beer (2015)

Many South African universities were included as part of collaborators for the South African AM Centre of Competence, AMCoC as shown in Figure 1.5 (Du Preez and De Beer, 2015). Furthermore, the AMCoC framework includes research councils, and South African-based companies that have a research and technology development strategy or vision in AM and are ready to collaborate with universities and research councils.

The additive manufacturing education and research activities within selected universities in South Africa (i.e. CUT, VUT, NWU, UJ and SU) respectively are further discussed in the next paragraphs below. However, in this chapter a brief review of AM education and research activities at SAs' universities are presented. More importantly, an up-till-date review paper on recent applications of AM education and research activities at (CUT, VUT, NWU and SU) was accepted for publication in an international of "Rapid Prototyping" journal as presented in appendix F.

According to Jordaan (2010) Central University of Technology has become involved in extensive AM research since 1997. CUT launched an AM centre known as 'Centre for Rapid Prototyping and Manufacturing, CRPM'. CRPM serves as a system of commercial centre and bridging the gap between the faculty, academia and industry. Jordaan (2010) explains that "CRPM embarked on a process of developing its infrastructure and skills-base in this area about ten years ago, at a time when there were only approximately three AM machines in SA and over the years, CRPM has become leader in AM technology in the South Africa". Jordaan (2010) stresses that through a concerted effort, there come the development and implementation of a unique business model for commercialization, which is in collaboration with several industrial partners from within the academic environment.

Jordaan (2010) describes the unique role of AM technology at CUT within the South African higher educational system as follows:

- A course in mechanical engineering, which is unique within the South African context,
- A highly specialized facility became available to the university, but also to the SA's manufacturing industry,
- A moderately successful generator of third-stream income was created,
- An opportunity was created for the development of a multi-disciplinary research activity in evolvable manufacturing systems, and
- An enhancement of the academic status of the university.

According to De Beer (2010) the Centre for Rapid Prototyping and Manufacturing at the CUT proved that enabling Rapid Manufacturing platforms can create the platform for Higher Education Institutions (HEIs) to operate as entrepreneurial universities (ENUs) in SA. CRPM does commercial and research work using rapid prototyping, rapid tooling, rapid manufacturing and more so, medical product development technologies. The prototypes produced at the CRPM are being used by industrial and product designers for final prototypes before mass production of tooling. CRPM uses plastic, metal and sand to manufacture prototypes. Figure 1.6 presents the process that CRPM is using to create prosthesis for medical implant, from the design phase (*creating the digital prosthesis*) to AM phase (*using direct metal laser sintering*) and to final prototype phase (CRPM, 2016).

Figure 1. 6: Process of Creating Prosthesis for Medical Implant, from Design to Final Prototype at CRPM.
Source: CRPM website (http://www.cut.ac.za/crpm/)

De Beer (2010) further explains that Vaal University of Technology (VUT) has a technology station where excellent research in AM is being carried out and the facilities at VUT function as a service bureau, supporting local industry and entrepreneurs, as well as providing research support to local and international researchers. Currently, in South Africa VUT offers the highest resolution polymer laser sintering (De Beer, 2010). The AM in-house facilities at VUT uses several technologies to manufacture prototypes and products from a range of machines. The facilities at VUT also offer a range of prototyping and manufacturing technologies, including 3D printing, fused deposition modelling (FDM) and laser sintering (LS). The AM facilities at VUT can create useable prototypes and final components quickly and accurately, in a range of materials (VUT, 2013).

The North-West University (NWU) has approximately 30 UP mini 3D printers at the “Pukke 3D Printing Centre” and in various locations/staff offices on the campus. The faculty of engineering also has an ultramodern and sophisticated AM machines worth R2.5 million at the university’s fabrication laboratory (FABLAB) for research and components development purposes; and in assisting academic staff and students for design of prototypes and one-off print. Presently, NWU faculty of engineering considered manufacturing of prosthetic limbs which can be sold for a fraction of market cost due to the concern for most people who have lost their limbs from a motor accident or any form of accident (NWU, 2017). The main aim of the project is to assist people for whom the arm or leg has been amputated and could not afford a prosthetic arm, limbs or leg due to a lack of funds. Recently, a master’s student in person of (Jako van Rooyen) worked on the design of a prosthetic arm and aimed to build a new plastic arm with the 3D printer at the University FabLab (NWU, 2017).

As part of AM research at the NWU, a PhD student (Sonette du Plessis) at Occupational Hygiene is currently working on a research title "The hazardous chemical substance exposure associated with AM processes". The study aimed to identify the health risks associated with all the additive manufacturing processes located at the Council for Scientific and Industrial Research (CSIR), VUT, CUT and SU. In a recent article by (*Mail & Guardian-online* in 2015), Sonette du Plessis explains that the study "will assess levels of exposure to the chemicals used in the processes and provides important information for training employees on the health consequences of being exposed to the materials used in AM and delivers control measures necessary to eliminate or reduce employee exposure".

The University of Johannesburg (UJ) has key academic researchers in the field of AM. Pieterse and Nel (2016) explained that "in 2008 the Mechanical Engineering department at the UJ purchased a "**Dimension Elite**" 3D printer to be used in students' design and research projects". According to Pieterse and Nel (2016) the opportunities for application of the 3D printing technology were immediately apparent in the area of design but not so for research projects. A review paper by Pieterse and Nel (2016) titled "The advantages of 3D printing in undergraduate Mechanical Engineering research"; concluded that the decision to use the '**Dimension Elite**' 3D printer in Mechanical Engineering department for the past 8 years for rapid prototyping models in mechanical engineering research projects have greatly benefited students in their ability to develop different experimental test setups". More so, in November 2017, the University of Johannesburg launched a "Makerspace laboratory" and the laboratory is equipped with five 3D printers and 3D scanning facilities, with smart computer technologies, and tools such as AstroPrint/OctoPrint. The recent AM/3D printing in-house facilities at UJ are accessible to both the staff members and students, and in addition, the creative engineering, technology, science and craft students have access to the facilities as well; and thereby boosting their AM/3D printing skills development (UJ, 2017).

Stellenbosch University has a long history of rapid prototyping and the university has a laboratory called "Rapid Product Development Laboratory (RPDLab)2. According to Dimitrov (2006) RPDLab is leading Stellenbosch University's effort to explore AM/3D printing value in manufacturing, prototyping, architecture and medicine. The research at RPDLab has provided SAs' industries with objective data on which to base manufacturing decisions (Dimitrov, 2006). Simultaneously, the work at the RPDLab exposes several students across multiple disciplines not only engineering degrees, but other science related disciplines in advancing their knowledge on AM technologies (Dimitrov, 2006). Dimitrov (2006) explained that the scope of possible uses for AM across the universities is only broadening as additional educational opportunities are uncovered. Moreover, Dimitrov (2006) supports the importance of AM in education, with the involvement of the students with RPDLab at Stellenbosch University which combines students' *involvement, industry partnership and high technology of AM.* Through RPDLab, students were involved in the private sector, especially when the university and industry partners involve in AM technology research and this has provided unprecedented education potential for the students (Dimitrov, 2006).

According to Dimitrov (2006) as part of this mission "Stellenbosch has performed 3D printing work for a nearby architectural firm. Students have created a physical model of the Durban Millennium Tower, a monument that identifies the port city of Durban in SA, in the same way that the Eiffel Tower signifies Paris". Dimitrov (2006) stresses that the SU students have used AM machines to make models of product like "cell phones, remote controls, underwater cameras, corkscrews, elaborate perfume models, innovative electrical plugs and the Eiffel Tower". Meanwhile, the university's medical school uses 3D printing technologies in converting CT and MRI scans data into 3D models for academic and clinical purposes, enabling students to examine anatomy without surgery or dissection (Dimitrov, 2006). It enables them to practise and plan skill-intensive procedures and treatments and is especially helpful for visualizing abnormalities such as tumours and birth defects. Students are working closely with a craniofacial specialist to create models of head and facial structures (Dimitrov, 2006).

Because of the growth and emerging development in the area of AM technology in South Africa, more research focus needs to be conducted within the universities system and through this medium both undergraduate and postgraduate engineering students would be introduced to AM education and technology; especially students within the STEM education. This will broaden their knowledge of industrial applications of AM. To have a successful implementation of South Africa AM technology roadmap, South African universities needed more partnership with AM industries in research (i.e. technology transfer between the university and industry). Jordaan (2010) defines "technology transfer as the process of passing theoretical and practical skills, knowledge, processes, technologies and manufacturing methods from the owner of a technology to a wider range of users in ensuring that scientific and technological developments become more widely available in industry while ensuring skills development of university academic staff". Therefore, technology transfer will bridge the gap between the industries and academia.

1.2 Problem statement

In the past few years, industrial applications of AM technology in South Africa are on low volume production. However, AM technology has gained significant attention in the academia as well as manufacturing industries due to its ability to create complex geometries with customizable material properties. AM is so relatively new, and the greatest impact may come through the introduction of AM education to university curriculum and AM technology to the local manufacturing industry in South Africa. As stated by Krassenstein (2014) one clear reason why AM technology has been quite slow in making its impact in educational institutions is simply because of the *lack of knowledge of the technology by the academics, students and the decision makers in charge of AM technology*.

Du Preez *et al.* (2016) explain that "as the AM technology grows in South Africa, the need for educated personnel in the field is becoming more apparent". In 2013, during a stakeholder workshops in South Africa, education was one of the main priorities identified to ensure successful adoption of the additive manufacturing technology in South Africa (Du Preez *et al.* 2016). The stakeholders include 105 people from industry, government, higher education institutions, 3D printing service providers and R&D institutes. Furthermore, Akinlabi (2016) stated that South Africa AM in the academia and undergraduate teaching is still at an infancy stage and 3D printing technology is a global technology with a lot of relevance in the industry and it is a multidisciplinary. Akinlabi (2016) also stresses that "there is a need for a group that will act as crusaders to champion its inclusion in the curriculum of the relevant courses for the country to fully reap from its enormous benefits".

Based on the perspective of Gungor Kara, the Director of Global Application and Consulting at EOS (Davies, 2017), stated that:

> *[Education is] the key element to access the full potential of the additive manufacturing technology. The situation in the past, the educational programmes [have been] connected to universities, and the professional training for experienced engineers in companies was missing.*

The problem is that *"as several manufacturing and industrial sectors are adopting AM technologies in South Africa, there is a need for more university graduates, most especially in science and engineering with fundamental or in-depth knowledge of AM technology to work with the emerging AM sectors or 3D printing service bureau in South Africa. It is very important to develop an effective framework for AM education for South African universities that will further promote AM education among students, academia and industry professionals".*

1.3 Research questions

According to Biddix (2009) a research question is the fundamental core of a research project, study, or review of literature. To effectively develop a framework for additive manufacturing education at South Africa universities, one main research question and four sub-research questions were formulated as stated below. The research question will be answered through literature reviews, observation and analysis of data collected:

The main research question:

Is there an effective framework for Additive Manufacturing education at South African universities to further promote AM education and research activities in the field?

Sub-research question 1

How are the key factors/variables in the development of a framework for effective AM education derived or identified?

Sub-research question 2

What is the perception of students and academics towards the inclusion of an AM education/course in science and engineering curriculum at South African universities?

Sub-research question 3

Are there supporting factors (sub-factors) that would influence a successful inclusion or implementation of AM education at the university in the proposed framework?

Sub-research question 4

What are factors necessary for sustainability of additive manufacturing technology within the educational sector and Is standardization of AM important to AM education?

1.4 Aim of the research

The aim of this study is to investigate the impact of AM technology at selected South African universities and to develop a framework for effective additive manufacturing education to further enhance the educational aspect of AM technology at South African universities.

1.5 Objective of the research

To achieve the overall aim of this research, the following objectives will be considered:

- To conduct a comprehensive literature study on additive manufacturing education, its applications in industries and academic; and the sustainability of additive manufacturing in education sector.

- To investigate the existing AM education, AM framework and AM curriculum through literature survey from a global perspective.

- To investigate the impact of AM technology and education using an empirical approach (quantitative method) for data collection among students and academics, to analyse the result and present the discussion and interpretation of the statistical analysis.

- To develop a proposed framework for effective AM education at South African universities.

- To provide conclusions, contribution to knowledge and recommendations for future work.

1.6 Research methodology

For effective research processes, data collection for this study and the development of a framework for AM education, the following research methodology was considered. In this chapter, complete details of the research methodology will not be discussed but the concept was described diagrammatically in Figure 1.7. However, each step of the research methodology would be fully discussed in detail in section 6.4 of Chapter 6 of this doctoral thesis:

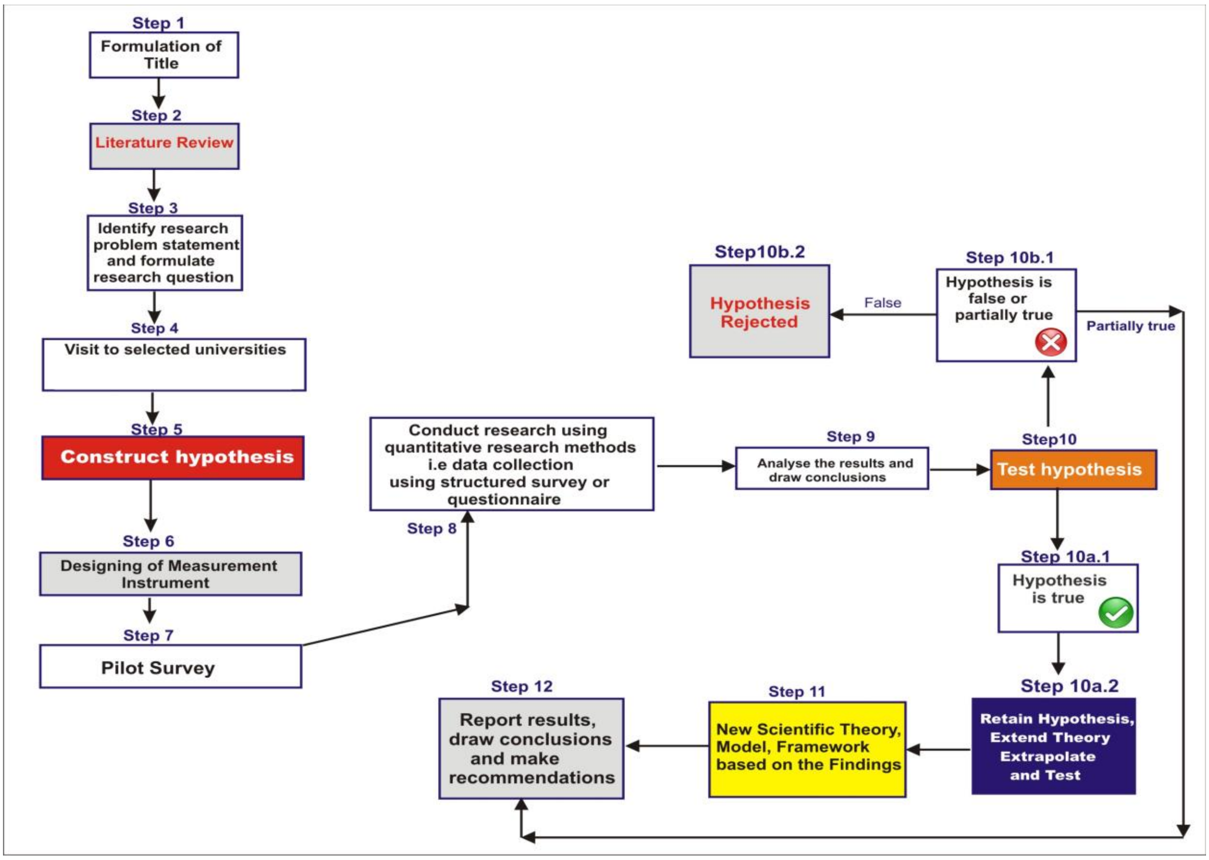


Figure 1. 7: Research Design/Methodology.
Source: Researcher's own construction

1.7 Scope of the research

Due to the diverse area of research within the AM sector in the world, the scope of this research is being limited to AM education with focus on South Africa universities.

1.8 Significance of the study

There are limited studies in AM that centre mainly on AM education. This study under investigation is unique because it is from a South Africa context. The study will contribute to the existing theory or research relating to AM education research. This would be achieved through the development of a framework for additive manufacturing education at the universities. This study would also assist the key players in AM technology and business to see the opportunities to invest in AM education at all educational levels (i.e. primary and high schools, colleges, and universities).

A significant and practical aspect of the proposed framework can be employed by Higher Education Institutions (i.e. colleges and universities) and role players in AM industry to guide the integration and implementation of AM technology in the educational sector. The proposed framework is expected to complement the existing South African AM Technology Road-map as mentioned in section 1.1.3 of this chapter; and the recently developed South African Additive Manufacturing Strategy (Du Preez *et al.*, 2016; Du Preez and De Beer, 2015).

1.9 Research layout

This doctoral thesis is divided into eight chapters; from the introductory chapter to the concluding chapter. The literature review aspect of this doctoral thesis is divided into four chapters to give room for comprehensive literature survey. Table 1.1 presents the research layout for this thesis which includes the titles, chapters and brief descriptions of each chapter.

Table 1. 1: The Research Layout

Titles	Chapters	Descriptions
Introduction:	**Chapter 1**	This chapter presents the research background, problem statement, research aim and objectives, method of investigation (research design/methodology) and the research layout is described with a brief explanation.
Literature Review:	**Chapter 2** Additive Manufacturing/3D	This chapter presents the general overview of AM education within the university context. This chapter extensively reviewed the existing framework on AM technology and not framework for AM education per see because as at the time

	Printing Technology in Education	of writing this thesis, there are no framework for AM education. Recent studies within the context of AM education was also reviewed. Furthermore, this chapter presents an overview of AM/3D printing laboratory concept at the universities and how entry-level FDM 3D printers can be used as a tool for AM education at the universities.
	Chapter 3 Additive Manufacturing Technology	This chapter introduces the global perspective of AM technology. The history of additive manufacturing, the economic impact of additive manufacturing and the challenges, opportunities and constraints of AM Technology. This chapter also presents the current applications of AM and its history of early adoption in South Africa.
	Chapter 4 Application of Additive Manufacturing Across Different Sectors	This chapter presents a comprehensive overview of various applications of AM technology across different sectors. This chapter also looks at the various contributions and technological advances that the universities, manufacturing industries, 3D printing companies, research institutes and research councils have contributed to enhance additive manufacturing growth and development over the years. The risk and uncertainty, and other considerations associated with the growth of AM were presented.
	Chapter 5 Sustainability of Additive Manufacturing in Education	This chapter presents a review of various scientific papers, publications and journals on “sustainability” as relating to additive manufacturing education and AM technologies. The key factors that were considered important for the sustainability of AM education is presented. More so, this chapter addresses how AM can serve as tool for sustainable product design. The chapter also presents the agreed-upon common structure of AM standards development is crucial for sustainable of AM education, research output, and universal product developing in the universities.
Research Methodology:	**Chapter 6**	This chapter presents the empirical investigation for this study and addresses the theory behind empirical investigation, scientific method, and development of questionnaire for survey. The different phases involved in the research methodology are also explained and the empirical findings. This chapter also explains the measuring instrument in detail and the relevant statistical approach needed for the statistical analysis; and discussion and interpretation of the analysed data.
Discussion and Interpretation:	**Chapter 7**	This chapter presents the discussion and interpretation of statistical analysis. The hypothesis was stated, verification and validation of the result is discussed. The chapter also presents a proposed framework for effective AM education at South African universities.
Development of the Proposed Framework for Additive Manufacturing Education	**Chapter 8**	The main aim of this thesis is to develop a framework for effective additive manufacturing education at the university. Therefore, this chapter presents the proposed framework for additive manufacturing education – a case study of South African universities. The chapter also presents the methods used in the verification and validation of the results.

Conclusions, Recommendations and Future Work:	**Chapter 9**	This chapter provides the general conclusion to the research based on the empirical results and findings. The aim, objectives and research questions were reviewed. Finally, the chapter presents the recommendations, limitation of the study, contribution to knowledge and possible future research work.

1.10 Chapter summary

This chapter presents an insight into the broader perspective of this study and serves as the introductory chapter for the remaining seven chapters. The research problem was identified; the research questions, the aim and the objectives were listed accordingly. The research methodology was shown diagrammatically. Based on different literature consulted, it shows that South Africa is making tremendous progress in AM research through the universities, collaborations from science and research institute including industry partners.

The next chapter presents a global perspective of AM technology and its technological innovations and advancement. The next chapter present the detail review of AM technologies and processes. The chapter also provides a brief history of AM and its history of earlier adoption in South Africa. A close look at the influences of AM technology as manufacturing concepts and innovative tools for future advancement will be investigated.

Chapter 2

2. Additive Manufacturing Technology

This chapter presents the literature review from various articles, journals, publications and open scientific repository on global perspective of AM technology. The history of AM and the economic impact of AM; and the challenges, opportunities and constraints of AM technology were presented in this chapter. This chapter also presents the seven AM processes as classified by ASTM standard F2792, from powder-based to liquid-based materials and finally, the current trends of AM adoption in South Africa were explored as well.

2.1 The term "Additive Manufacturing" technology

Additive manufacturing (AM) enables the fabrication of parts and devices that are geometrically complex, have graded material compositions, and which can be customized (Rosen, 2007). According to Jing *et al.* (2014) AM is the digital manufacturing technology by which products are fabricated directly from computer models by selectively curing, depositing or consolidating materials in successive layers. Jing *et al.* (2014) further explain that AM technology has provided an opportunity to rethink the methods of product design to maximize the product performance through the synthesis of material compositions, structure, and sizes.

In 2012, Brent Stucker, an internationally recognized AM expert, in his book defines AM techniques as a collection of manufacturing processes that join materials to make physical 3D objects directly from virtual 3D computer data. Stucker (2012) explains that AM processes typically build up parts layer by layer, as opposed to subtractive manufacturing methodologies, which creates 3D geometry by removing material in a sequential manner. Stucker (2012) further says "In 2009, after more than 20 years of confusing terminology, the ASTM International F42 Committee on Additive Manufacturing Technologies defined AM as the [process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies]". AM technology is also referred to as - 3D printing technology, rapid prototyping, direct digital manufacturing, solid freeform fabrication, additive fabrication, additive layer manufacturing, and other similar technology names over the years.

According to Stucker (2012) every existing commercial AM system works in a similar way, firstly, a 3D computer-aided design (CAD) file is sliced into a stack of two-dimensional planar layers and these layers are built by the AM machine and stacked one after the other to build up the parts. AM machines/3D printers work in the same manner as inkjet printers, but the difference is, that inkjet printers use ink while 3D printers use specific desired materials to create physical object from a digital file (T. Rowe-Price, 2013).

Over the last 15 years, AM has created a competitive advantage for many manufacturing and industrial companies in their pursuit of operational efficiency in their daily productions (Harris, 2011). AM has many advantages when compare to conventional manufacturing processes. For instance, 3D printing has the ability to manufacture complex forms and shapes (Vayre *et al.,* 2012). AM gives designer a freedom to design the part according to his/her own specifications and helping engineers or 3D printers (3DP) experts to produce lightweight structures (Vayre *et al.,* 2012).

AM is not only making its advancement in the manufacturing and industrial sectors but also making its way into other sectors such as medical, tooling, aerospace, architecture, dental, electronics, commercial and consumer products, automobile, education, etc. *Bull et al. (2010) used the education sector as an example and explain that "the integration of AM into the engineering and manufacturing curriculums has greatly enhanced student's level of learning*". Kroll and Artzi (2011) supports Bull *et al.'s* (2010) opinion that the students now have the ability to be more responsive and creative in their learning challenges because they make use of visualizing concepts rather than the usual reading technique of studying. Therefore, educators and academics can harness the AM technology to encourage scientific thinking, and as a means to develop the real-world skills (Menezes, 2013). The aerospace industry employs AM technology because of the possibility of manufacturing lighter structures to reduce weight. More so, AM is also transforming the practice of medicine and making work easier for the architects (Wong and Hernandez, 2012) and the list is endless.

Additive manufacturing is a manufacturing process that supports every area of the product development cycle, starting from the design concepts to prototype and the production of the final parts. According to Denning (2012) as relating to product development, AM has given many companies a way to limit outsourcing to third parties by developing concepts in-house. Kochan (2000) describes AM as a technology that has created an advantage over competitors by shortening the product development cycle. Figure 2.1 below presents a typical AM product development cycle, that is, the designer will come up with a design concept, and the design concept passed through computer-aided design (CAD). Thereafter, computer-aided engineering (CAE) software simulate the performance in order to improve the product design; then the rapid prototyping (RP) phase has been achieved; the prototype will be tested and evaluated; and if the design criteria or specification is met, and the final product will be printed from the AM machine.

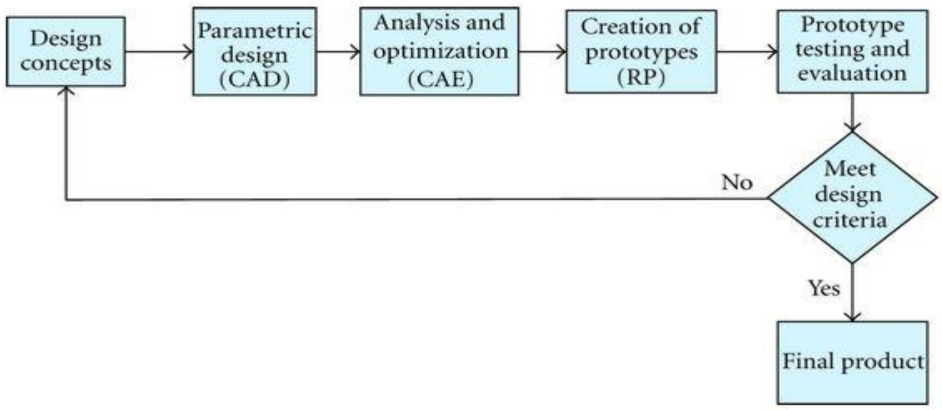


Figure 2. 1: Additive Manufacturing Product Development Cycle. (**Source:** Noorani, 2006)

According to Lu *et al.* (2015) AM technology has been developing rapidly in the last three decades and this shows great potential for the future development of AM. The promising future of AM makes its impact on the traditional industry unpredictable (Lu *et al.*, 2015). The full potential of AM will not be realized until there is a broad integration of the technology into so many manufacturing solutions. AM has the potential to vastly accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste (AMO, 2012). Huang and Leu (2014) stated that AM technology has experienced significant development and it still not widely accepted by most industries across the globe. Huang and Leu (2014) explains the need to critically improve AM technology to the point of changing people's mind-set in next couple of years and thereby gaining industry acceptance, and to broaden, develop, and identify manufacturing applications that have being greatly improved AM processes.

From *university-industry collaboration and technology transfer perspective*, Huang and Leu (2014) emphasize the numerous efforts of AM developers and academic researchers and say more and more companies have begun to use AM technology to reduce time-to-market, increase product quality, improve product performance, and reduce product manufacturing costs. Furthermore, from a global perspective, several AM processes have been introduced to the commercial market by industrial companies like Electro Optical Systems (EOS) in Germany, Arcam in Sweden, MCP Tooling Technologies in the U.K, Stratasys, 3D Systems, and Optomec in the U.S and among others (Huang and Leu, 2014). In conclusion, AM poised to attract many research interests within the academic sectors and global manufacturing industries in the next 10-30 years.

2.2 History of Additive Manufacturing

Cotteleer *et al.* (2014) emphasize that "AM has its earliest roots in research activities from the fields of topography and photosculpture during the 19^{th} century; and the first successful attempt at AM derived from the technology developed in the 1970s". According to Wohlers and Gornet (2014) AM was first emerged in 1987 with stereolithography (SL) from 3D Systems, which is a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser.

The first commercial AM system available in the world was SLA-1, and it was the precursor of the once popular SLA 250 machine which was known as StereoLithography Apparatus. After many years, Viper SLA product which was designed by 3D Systems replaced the SLA 250 (Wohlers and Gornet, 2014). The Ciba-Geigy and 3D Systems partnered in SL materials development in 1988 and they commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machines and materials were developed in 1988. In the late 1980s, Loctite entered the Sl resin business and remained in the industry only until 1993 (Wohlers and Gornet, 2014).

The introduction of non-stereolithography (non-SL) system came into existence in 1991, three AM technologies were commercialized, and they are Fused Deposition Modelling (FDM) designed by Stratasys, Solid Ground Curing (SGC) made by Cubital and laminated object manufacturing (LOM) made by Helisys (Wohlers and Gornet, 2014). Wohlers and Gornet (2014) reported that "FDM extrudes thermoplastic materials in filament form to produce parts layer by layer while SGC used a UV-sensitive liquid polymer, solidifying full layers in one pass by flooding UV light through masks created with electrostatic toner on a glass plate and LOM bonded and cut sheet material using a digitally guided laser. Cubital and Helisys have not been in business for many years".

Low-cost AM systems or 3D printers were introduced in 1996, when Stratasys introduced the Genisys machine and the machine used an extrusion process which was similar to FDM but based on technology developed by IBM's Watson research centre (Wohlers and Gornet, 2014). Wohlers and Gornet's (2014) stated that "After eight years of selling stereolithography systems, 3D Systems sold its first 3D printer (Actua 2100) in 1996, using a technology that deposits wax material layer by layer using an inkjet printing mechanism". In 2000, a new generation of AM system was introduced, that is, Objet Geometries of Israel announced Quadra; which is a 3D inkjet printer that deposited and hardened photopolymer using 1,536 nozzles and a UV light source (Wohlers and Gornet, 2014).

According to Cotteleer *et al.* (2014) AM processes were largely geared toward prototyping applications in the 1990s. During late 1990s, AM technologies and processes were increasingly employed in large-scale industrial, medical and consumer end-market application (Cotteleer *et al.,* 2014). In the early 2000s, significant development was recorded in the applications of AM technologies and such development includes production of parts for unmanned aircraft, automobiles, consumer products, and medical sectors i.e. printing of tissue and organ systems (Gibson *et al.* 2010) as stated by (Cotteleer *et al.,* 2014). At present, AM continues to improve its speed processing, complexity of design and the variety of materials used (Cotteleer *et al.*, 2014)

2.3 History of earlier adoption of Additive Manufacturing in South Africa

According to De Beer (2011) South Africa's rapid prototyping (RP) which is known as 'Additive Manufacturing' activities took off approximately 10 years after the international community had accepted the technology and this implies that South Africa started from a position that was lagging behind other industrialized countries. De Beer (2011) stated that "in 1991, the first AM system (3D Systems SLA 250) was introduced into South Africa and this was followed by two FDM 1500 machines and which were later upgraded to FDM 1650s and these machines were owned by the Council for Scientific and Industrial Research (CSIR)".

In 1996, the Central University of Technology (CUT) purchased a Sanders ModelMaker II and an SLA 250 and in the same year, the Council for Scientific and Industrial Research installed an SLA 500. In 1998, the CUT purchased a DTM Sinterstation (now 3D Systems) and this brought the number of AM machines in South Africa to seven. Out of the seven AM machines available in South Africa in 1998, six of the AM machines were owned by the academic or research institutions except SLA 250 which was owned by a private company (De Beer, 2011). AM was initially introduced into the higher education (universities) and other research institutions with the aim of assisting their cooperation with the industry (De Beer, 2011). Campbell and De Beer (2005) added that "the diverse and complementary nature of the AM machines installed allowed active collaboration, efficient planning and conducting of research programmes".

According to Campbell and De Beer (2005: 261), further steady growth took the overall number of AM machines in 2003 to 17 with only two in private company as reported by (Wohlers, 2004). In 2004, AM implementation within South Africa began to follow a new shift or direction and since 2004, the trend towards AM/3D printing technology has continued to grow in South Africa (Campbell and De Beer, 2005:261) and the market of AM systems in South Africa has increased from 1500 in 2013 to 3500 in 2015 as shown in Figure 1.1 in chapter 1 (De Beer, 2015b).

In 2000, the Rapid Product Development Association of South Africa (RAPDASA) was officially launched and RAPDASA has played a significant role in raising awareness through annual conference and international ties such as the Global Alliance of Rapid Prototyping Associations (Kunniger, 2015). De Beer (2011) explains that "through RAPDASA's intervention and support, industry members also became part of the research community, and contributed to the South African AM community's research outputs, both in terms of conference or journal papers, as well as in terms of formal conducted research projects". According to De Beer (2011) to some extent, a bit of a drawback was the fact that the AM base in South Africa had to serve a very wide and diverse range of application areas, which includes - automotive components, anthropological studies, jewellery masters, medical visualization, industrial design models, architectural models, low-volume tooling and rapid manufacturing of functional parts.

The South African government started investing in AM technology in the early 1990s and the government has spent approximately ZAR 358 million (EUR 22 million) on AM/3D printing technology research and development between 2014 and 2016. In addition, the Department of Science and Technology set to commit another ZAR 30.7 million (approximately EUR 2 million) towards a collaborative research and development programme in AM (Williams, 2016). Williams (2016) also stresses that "the collaborative research and development programme will focus on R&D and innovation support in AM of titanium medical implants and aerospace components and polymer AM in design,". More so, the DST seeks "to increase the adoption of AM as an accepted and viable manufacturing technology in South Africa. This investment has imbued SA with specific world-class capabilities, positioning the country to participate in sub-sectors with high growth potential in AM, such as aerospace applications and medical and dental devices and implants." (Williams, 2016). According to Williams (2016). South Africa needs to invest wisely in this AM technology and says that "it is imperative for the public and private sectors to coordinate and synergise efforts in the identified niche areas where we have or can create a competitive advantage".

Recently, SA has developed a new high speed and large volume AM system for metal parts and the system was developed in partnership by the National Laser Center (NLC) at the Council for Scientific and Industrial Research (CSIR) by Aerosud, a South African Aerospace company (Science-Forum, 2015). National Laser Centre and Aerosud aimed to develop AM techniques and the world's largest 3D printer (Wild, 2014). The project is called "Aeroswift" which was fully funded by South African Department of Science and Technology (Science-Forum, 2015).

De Beer (2011) maintains that from South Africa AM roadmap, it is very obvious that additive manufacturing has developed into an established technology platform in South Africa. Based on De Beer (2011) report, currently, 91% of the available AM/3D printing machines in South Africa are in the industry, with most of the high-end machines (industrial grade AM machines) in research institutions. Campbell *et al.* (2011) conducted a similar analysis up till 2008 and the analysis shows that all the major universities in South Africa have a strong presence in manufacturing-related research. According to Campbell *et al.* (2011) approximately 48% of all South African universities now have AM facilities in-house. However, Campbell *et al.* (2011) further says that "AM research is still only pursued by 39% of the South African universities while 9% of the South Africa universities have AM in-house facilities that supports other manufacturing research related.

Wild (2014) concludes that South African Department of Science and Technology together with research council (i.e. CSIR), academia and industry have developed an AM technology road map which is going to plot the journey/course for South African companies and manufacturers in this "new revolution". Conclusively, De Beer (2011) says that South African became a benchmark for other countries who are late adopter of AM to follow, that is, "as slowly a position of following became a position of leading through innovative applications" (De Beer, 2011).

2.4 The Benefit of Additive Manufacturing

During a roundtable discussion which was held in May 2013 by the Royal Academy of Engineering (RAE) to discuss the condition of the UK's AM sector. The meeting allows the attendees (i.e. researchers and industry experts) to identify various advantages that AM offers industry and these advantages were summarized in three words that is – [*Efficiency, Creativity and Accessibility*]. AM technology has a unique processes and techniques that creates new ground for innovations and it also offers a range of logistical, economic and technical advantages (RAE, 2013). Other significant advantages and benefits of AM that was identified during RAE roundtable discussion were listed in Table 2.1 with brief discussions.

Table 2. 1 : The advantages of additive manufacturing. (Source: RAE, 2013).

S/N	The advantages of AM	Discussions
1.	Low-volume production	AM provides cheap, low-volume production and facilitates personalised and customized products. For instance, AM replaces machine tooling. According to Professor Richard Hague, Director of the EPSRC Centre for Innovative Manufacturing in AM; from his perspective “Customisation as a real business opportunity, especially in the healthcare sector”. AM makes customization of various design model accessible to everyone.
2.	Lower-cost production	One of the advantages of AM over traditional (subtractive) machine tooling is the lower cost of manufacture. In Kenny Dalgarno’s opinion, a Professor of Mechanical Engineering at the Newcastle University, and he said that “The fact that AM can make manufacturing cheaper is important in pushing the technology out to businesses”. Hybrid production incorporating AM can help reduce its outlay on the high value Material and a lead time benefit for the raw material
3.	Responsive production	AM offers faster lead times than subtractive (traditional) manufacturing techniques especially for a low-volume production, “for instance - Formulae One motor racing, the engineers are using AM to manufacture parts in a highly reactive way”. Graham Tromans, Principal and President of AM Consultancy supports the above examples as relating to Formulae One motor and he said, “They can now analyse the car’s performance while it goes around the circuit and have a new part getting ready before it finishes the race,”
4.	Shorter supply chains	AM has the capacity to simplify and shorten the manufacturing supply chain. According Graham Tromans during the roundtable discussion at the Royal Academy of Engineering, he uses an on-site manufacturing technique to explain supply chain in AM technology and he said, “If you are manufacturing these parts on site then you don’t need transportation, and you remove unnecessary international shipping, so manufacture is nearer to the consumer”. This has created opportunities for local, regional or national manufacturing centres, and many of them already supports on-site rapid prototyping.
5.	Democratisation of production	Democratisation of production is a mean through which more people having access to a new rapidly growing technology. AM technology allows the creation of more complex objects, which would compel users to think back to first principles and asking, ‘what is it that this object is trying to do?’ rather than ‘how do I make this one better than the last one?’. AM may require more skills of people and AM experts, and not less; because it gives room for further thinking to improve any existing design models. Robinson (2014) explains that “3D-printing allows consumers to turn highly individualized concepts or designs into real-life products via a “personal manufacturing” process. As 3D-printing services and consumer devices become more affordable and ubiquitous, companies will start making digital versions of their products and parts available and consumers will be able to download, modify and print these digital versions directly.”
6.	Optimised design	According to Dr Chris Tuck, an Associate Professor of AM and 3D printing research group at the University of Nottingham, during the roundtable discussion at the RAE; he explains the capacity of AM which allows “fundamental rethinking and redesign of products” and this can result in better components. AM allows the construction of more complex geometrics than traditional manufacturing methods. For examples, injection moulding - this makes it possible to create pre-assembled AM with multiple moving parts. AM allows design optimization, and this improve the design performance, its reliability and the rationality of the weight (RAE, 2013).

In conclusion, to make the most of the potential of AM techniques, industrial designers and manufacturing experts have to adapt their production approach to AM technologies and this will result in moving away from the idea of replicating what is already made in other ways (RAE, 2013). It was suggested at the Royal Academy of Engineering discussion forum in 2013 that "designers are free to move away from creating things that can be computer numerical controlled (CNC) machined and should not be constrained by the idea that things have to be built up in layers".

2.5 Additive Manufacturing Opportunities and Challenges

According to Cotteleer *et al.* (2014) the United States has called for the creation of the National Additive Manufacturing Innovation Institute, and this call was mentioned during President Barack Obama's State of the Union address in 2013. The National Additive Manufacturing Innovation Institute has been established and it is now called "America Makes". This initiative is being funded in part by the United States government to help strengthen or re-energy the US manufacturing sectors (Cotteleer *et al.*, 2014). In the coming years, AM has the potential to shift United States manufacturing paradigm which implies that AM can allow US to become self-sufficient as production becomes localized (Cotteleer *et al.*, 2014). Some AM experts have identified AM as the next great disruptive technology which can be compared to a personal computer (PC) where globally, everyone on the earth could have the ability to imagine, design and create custom and personalized products (Cotteleer *et al.*, 2014).

Despite the fact that 3D printing technology has great potential to transform the manufacturing industries, AM technology is still having lot challenges. Cotteleer *et al.* (2014) look at the opportunities and challenges of AM from United States manufacturing perspective as seen in Table 2.2. The key market opportunities and challenges of AM were pinpointed. Cotteleer *et al.* (2014) says the lists are inexhaustible but it may serve as the basic for more thorough examination of the drivers and head winds that may impact future development in AM.

Table 2. 2: Additive manufacturing market opportunities and challenges (Deloitte analysis, 2013)

OPPORTUNITIES	CHALLENGES
• Unprecedented design flexibility, allowing customization and new product development	• Exuberance vs. natural evolution and true potential of the technology
• Consumerization/personalization of manufacturing	• Ethical considerations (e.g. guns, bioprinting of human cells)
• Novel end-market applications in areas such as regenerative medicine	• Intellectual property/privacy issues

• Relocalization of manufacturing	• Regulatory uncertainty in different countries
• Rapid product development and deployment	• Limited choice of materials
• Improving process sustainability (fewer yet greener materials; less energy and waste associated with production)	• Materials and process manufacturing qualification and certificate standards. Small production runs and scalability limitations.

2.7 Additive Manufacturing versus Traditional Manufacturing

According to Grynol (2013) due to the distinctive manufacturing processes of AM technology, people now have the ability to innovate products from the inside out. The process cannot be imitated using traditional manufacturing methods, because 3D printing is an additive process. AM allows individual and businesses to create the same internal skeletal structures and unique shape using the same object, (Grynol, 2013). Most times, economic growth entails new innovation and for new innovation to be emerged in any nation; there is a need to embrace technological-advanced manufacturing potentials. It is very essential for manufacturers and companies across many industries globally to develop AM capabilities for continuous innovation (Grynol, 2013).

Traditional manufacturing still holds an important place in the business world, and it is very challenging for AM technology to match the economies of scale available that traditional manufacturing holds (Grynol, 2013). Figure 2.2 compares the costs of producing the final product through traditional manufacturing techniques versus AM, and one very advantage that AM holds over traditional manufacturing is its ability to produce low number of final products at a very low cost while traditional manufacturing requires higher volumes of end-user products (Grynol, 2013). The vertical axis shows the "Cost Per" unit and the horizontal axis shows the "output" of both AM/3D printing and the traditional manufacturing as shown in Figure 2.2.

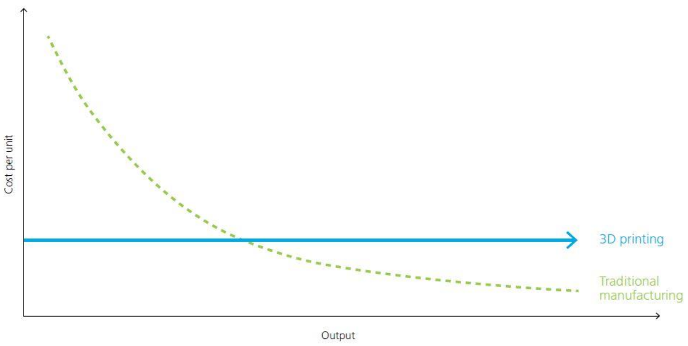


Figure 2. 2: Production Volumes versus costs: Traditional manufacturing versus AM/3D Printing

Source: Grynol (2013)

Grynol (2013) explains that "as those economies of scale come into play, traditional manufacturing can be more beneficial for producing larger quantities of products". In 2015, ATkearney documented a report on 3D printing as a manufacturing revolution and it was stated that traditional manufacturing has cost advantage in large-scale productions and argued that AM will also grow in the future in terms of lead time and speed, mass customization, and waste reduction. Grynol (2013) looks at the differences between AM and traditional manufacturing from their innovative nature and explains that traditional manufacturing often leads to evolutionary innovation while AM could lead to revolutionary innovation as shown in Figure 2.3. Grynol (2013) refers to evolutionary innovation as incremental and frequent in nature, that is, evolutionary innovations are those that results in creating new attributes and the customers expect these attributes to be developed eventually within the market. Revolutionary innovation refers to as a radical and less frequent in nature; for instance, a revolutionary innovation does not typically affect the existing markets, because the innovation being offered in the market is completely new to customers or end-users (Grynol, 2013). The vertical axis shows the "significance of innovation" and the horizontal axis shows the "output" of both AM/3D printing and the traditional manufacturing from both revolutionary and evolutionary perspectives as shown in Figure 2.3.

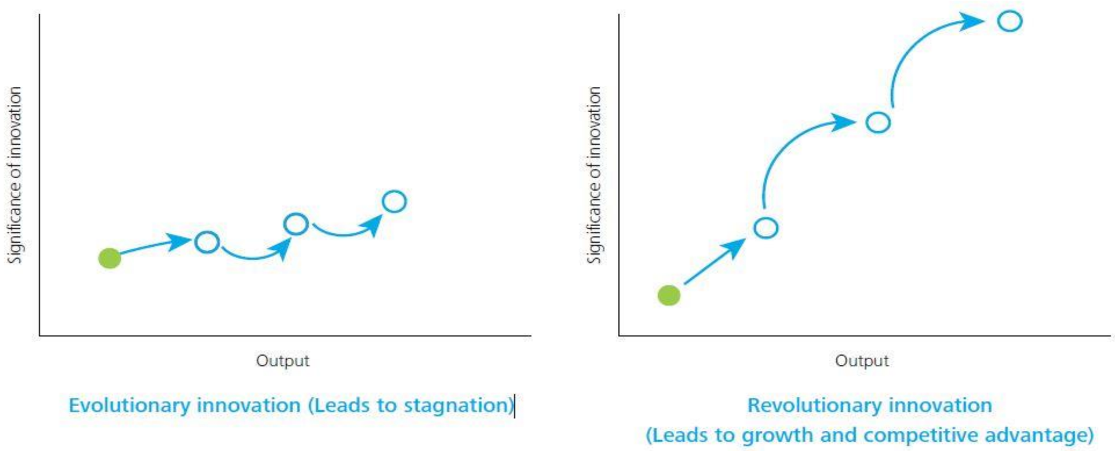


Figure 2. 3: Innovative nature of traditional manufacturing compare to additive manufacturing

Source: Grynol (2013)

In addition, Stratasys report in 2015 looked at the differences between AM and traditional manufacturing from another perspectives and the reports stated that "AM has filled an innovation gap left by traditional manufacturing techniques and AM is a complement to traditional manufacturing and will not replace traditional manufacturing in the foreseeable future but rather complement traditional manufacturing in the following areas (CNC machining, investment casting, hard tooling and injection moulding capabilities, providing more advanced and sophisticated manufacturing solutions)".

2.8 An overview on the seven additive manufacturing processes classification

According to ASTM Standard F2792 (2012) as cited by Gao *et al.* (2015) ASTM international recently classified AM technologies into seven categories as shown in Table 2.3 namely: (material extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition). The work of the American Society for Testing and Materials (ASTM) international committee F42 on AM technologies centres on promoting knowledge, research stimulation, and technology implementation through the development of standards. The seven categories or classifications of AM processes are listed in the Table 2.3 below with brief description including the related technologies, materials types and the companies that designed the technologies.

Table 2. 3: Classification of additive manufacturing processes by ASTM Standard F2792 (2012)

Process Type	Brief Description	Related Technologies	Companies	Materials
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Electron Beam Melting (EBM), Selective Laser Sintering (SLS), Selective Heat Sintering (SHS), and Direct Metal Laser Sintering (DMLS)	EOS (Germany), 3D Systems (US), Arcam (Sweden)	Metals, Polymers
Directed Energy Deposition	Focused thermal energy is used to fuse materials by melting as the material is being deposited	Laser Metal Deposition (LMD)	Optomec (US), POM (US)	Metals
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	Fused Deposition Modelling (FDM)	Stratasys (Israel), Bits from Bytes (UK)	Polymers
Vat Photopolymerization	Liquid photopolymer in a vat is selectively cured by light activated polymerization.	Stereolithographys (SLA), Digital Light Processing (DLP).	3D Systems (US), Envisiontec (Germany)	Photopolymers
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials	Powder Bed and Inkjet Head (PBIH), Plaster-based 3D printing (P3DP)	3D Systems (US), ExOne (US)	Polymers, Foundry Sand, Metals

Material Jetting	Droplets of build material are selectively deposited	Multi-jet modelling (MJM)	Objet (Israel), 3D Systems (US)	Polymers, Waxes
Sheet Lamination	Sheets of material are bonded to form an object	Laminated object manufacturing (LOM), ultrasonic consolidation (UC)	Fabrisonic (US), Mcor (Ireland)	Paper, Metals

2.9 Types of additive manufacturing/3D printing technologies

Several types or methods of AM/3D printing technologies have been designed in the past three decades and the differences in these technologies are based on the way layers are being deposited to create parts and types of materials used (HS3DP, 2016). These methods are categorized as stated below:

- Powder-based techniques – This method makes use of a melted or softened material to produce layers, for example (Direct Metal Laser Sintering, DMLS; Selective Laser Sintering, SLS; Electron Beam Melting, EBM).
- Liquid-based techniques – This method makes use of cure liquid materials with the help of different sophisticated technologies (Stereolithography, SLA or SL; Digital Light Processing, DLP; Fused Deposition Modelling, FDM).
- Sheet lamination techniques – Laminated Object Manufacturing (LOM) is a sheet lamination technology that uses sheets of raw material such as (plastic, paper, or metal laminates, ceramic, polymer film, etc.) which are successively glued or fused together and cut to shape with a laser cutter. Another example of sheet lamination technology is ultrasonic consolidation (UC) (Jasveer, 2018; 3D Print-Expo, 2017).

2.9.1 Additive manufacturing technologies – Powder-based methods

In this section, two AM technologies that uses powder-based method, with a brief discussion on how technology works, and a diagram to further illustrate each AM technology.

- **Direct Metal Laser Sintering (DMLS)**

According to Nyrhila *et al.* (2010) Direct Metal Laser Sintering (DMLS) is an additive laser melting technology that can be used for manufacturing functional metal components and tools in various alloys including light metal alloys, high grade steels, stainless steels and nickel and cobalt based super alloys. For many years, various industries such as (rapid tooling, medical and aerospace) have utilized DMLS methods for parts prototyping. DMLS was introduced in 1995 and it was the first commercial process for direct processing of metal powders (Nyrhila *et al.*, 2010). The typical processes involved in DMLS technology is described diagrammatically as in Figure 2.4.

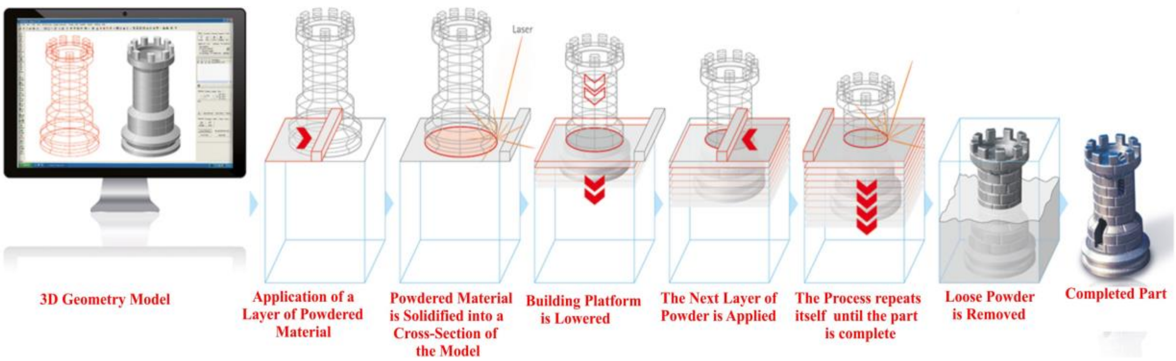


Figure 2. 4: Description of the DMLS technology. (**Source**: EOS, 2016)

DMLS uses digital 3D design data to build up a component in layers by depositing metal material. The system works by applying a thin layer of the powder material to the building platform and after each layer, a laser beam then fuses the powder at exactly the point defined by the computer-generated data using a laser scanning optic (Grünberger and Domröse, 2015). The platform is then lowered, and another layer of powder is applied and once again the material is fused so as to bond with the layer below at the predefined point resulting in a complex part i.e. the process repeats itself until the part is completed. The unused powder material is removed, and the final part or finished part is produced, and this makes DMLS technology unique (Grünberger and Domröse, 2015).

DMSL technology has two different methods of application namely, [powder deposition and powder bed methods]. These two methods are differing only in the way in each layer of the powder are applied. Powder deposition method uses metal powder in a hopper and melt the powder and a thin layer is being deposited onto a build platform while powder bed method uses powder dispenser piston that raises the power supply and then a re-coater arm distributes a layer of powder onto the powder bed and then a laser sinters the layer of the metal powder (CustomPartNet, 2009). Figure 2.5 shows the schematic diagram of DMLS technology including a typical DMLS 3D system.

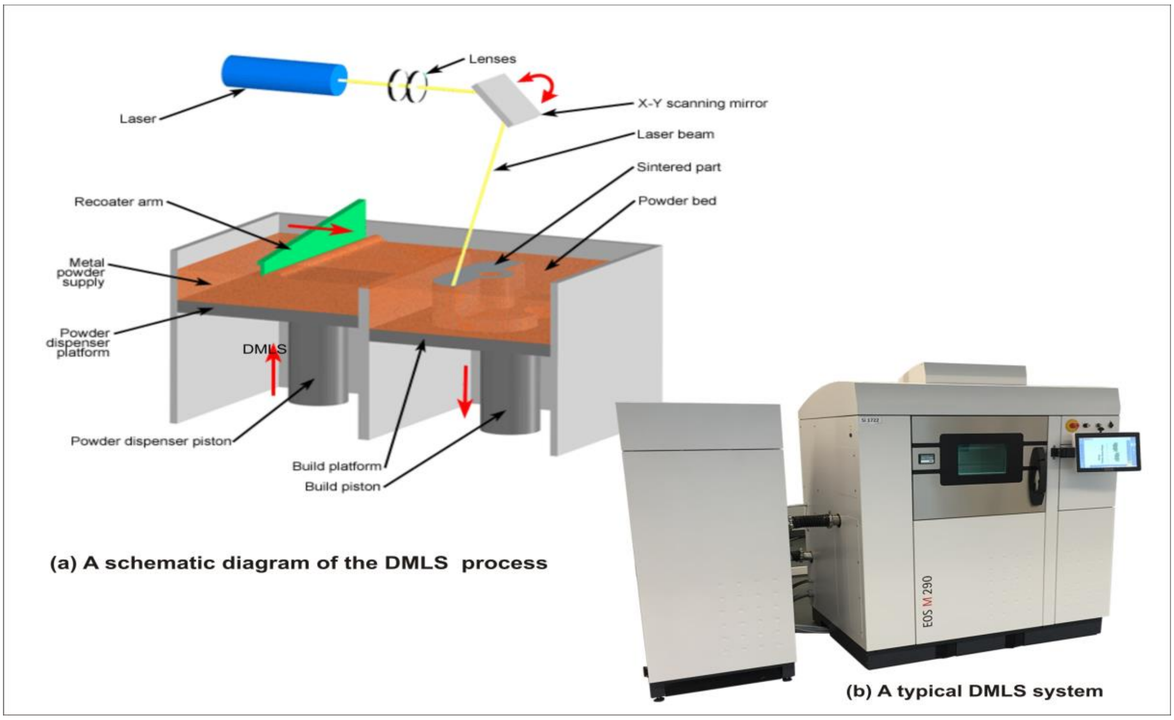


Figure 2. 5: Direct metal laser sintering AM technology. (**Source:** CustomPartNet, 2009)

- **Selective Laser Sintering (SLS)**

According to Miszalok (2009) Selective Laser Sintering uses a high-power carbon dioxide laser to fuse small particles of plastic, metal, or ceramic powders into a mass representing a desired 3-dimensional object. Miszalok (2009) further explains that "the laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part. For example, from a (CAD file or scan data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one-layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed". Schmid *et al.* (2014) stress that one problem limiting the application of SLS for AM in a wide-ranging of industrial sector is the narrow variety of the applicable polymer.

Schmid *et al.* (2014) identify polyamide 12 (PA 12) as the commonly used SLS powder and PA 12 is a dry blend and it is approximately 90% complete industrial consumption. SLS manufactures plastic parts by adding consecutively material layers and the technology is considered as the most suitable approach for plastic parts production which is appropriate for the industry (Schmid *et al.*, 2014). SLS has the capability of producing high durable part for real-world testing and mould making. SLS are very robust and can compete with traditional manufacturing techniques such as injection moulding. SLS technology is used for variety of end-use applications, for example, in the automotive and aerospace industries (3DSYSTEMS. 2016).

One significant advantage of using SLS is that, it does not need a support structure as other AM technologies require to prevent the 3D object from collapsing during production, because the product lies in a bed of powder (3DSYSTEMS, 2016).

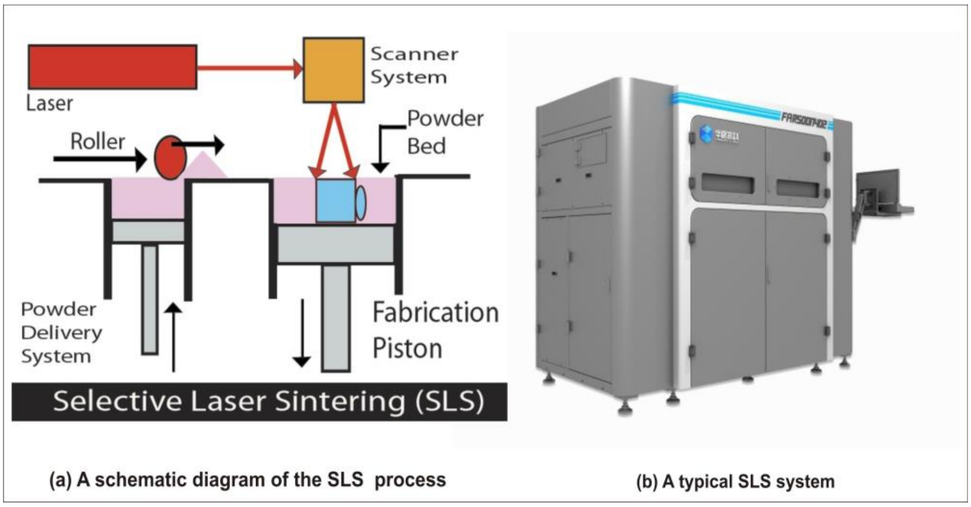


Figure 2. 6: Selective Laser Sintering AM technology. (**Source:** 3DPS, 2015)

- **Electron Beam Melting (EBM)**

Electronic Beam Melting is an AM technology that uses a metal powder-based process and it melts and forms a 3D part layer by layer by an electron beam which is under a high vacuum atmosphere (Klöden, 2016). According to Hiemenz (2007) Electron Beam Melting is a rapid manufacturing process where the fully dense parts with properties equal to those of wrought materials are built on a layer by layer basis. After melting and solidifying one layer of titanium powder, the process is repeated for subsequent layers until the part is completed (Hiemenz, 2007). EBM is a unique prototyping and manufacturing process that can simultaneously reduce costs, weight, and time (Hiemenz (2007).

Industries like aerospace, automotive and medical engineering are using this technology for both prototyping and low volume production of titanium parts. For instance, the aerospace industry uses EBM to produce (turbine blades and pump impeller), while automotive industry uses EBM technology to produce (turbo charger wheel) and also, the medical engineering uses the EBM for (medical implant). Presently, the most widely used materials for EBM are commercially pure Titanium, Inconel 718 and Inconel 625; and the processes are usually conducted under high temperature of up to 1000 °C (3DPS, 2015). Figure 2.7 describes EBM technology using schematic diagram.

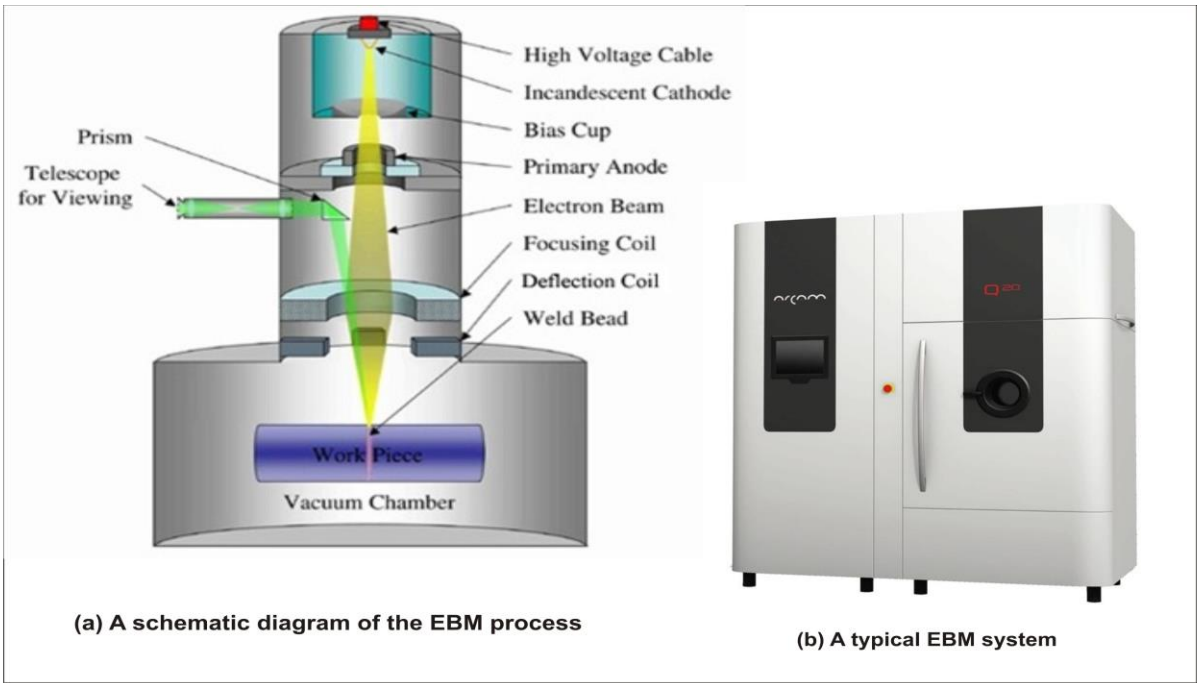


Figure 2. 7: Electron beam melting AM technology (**Source:** 3DPS, 2015)

2.9.2 Additive manufacturing technologies - Liquid-based methods

This section presents the liquid-based methods, each technology was explained with the aid of a schematic diagram and with a brief description of how the technology works.

- **Stereolithography (SLA/SL)**

Stereolithography is an AM technology that makes use of a vat of liquid ultraviolet curable photopolymer known as “Resin” with an ultraviolet laser to build part in layers one at a time (Anon, 2016). It is known as Stereolithography Apparatus (SLA) which converts liquid plastic into solid objects. It is the oldest method used to create 3D-printed objects (HS3DP, 2016). Stereolithography uses a platform which is lower into the resin through an elevator system, and the surface of the platform is a layer-thickness below the surface of the resin.

Therefore, the laser beam traces the boundaries and fill in a two-dimensional cross section of the models and wherever it touches, the resin is being solidified as described in the Figure 2.8 (HS3DP, 2016). Once a layer is complete, the platform descends a layer thickness, resin flows over the first layer, and the next layer is built. This process continues until the model is complete (HS3DP, 2016).

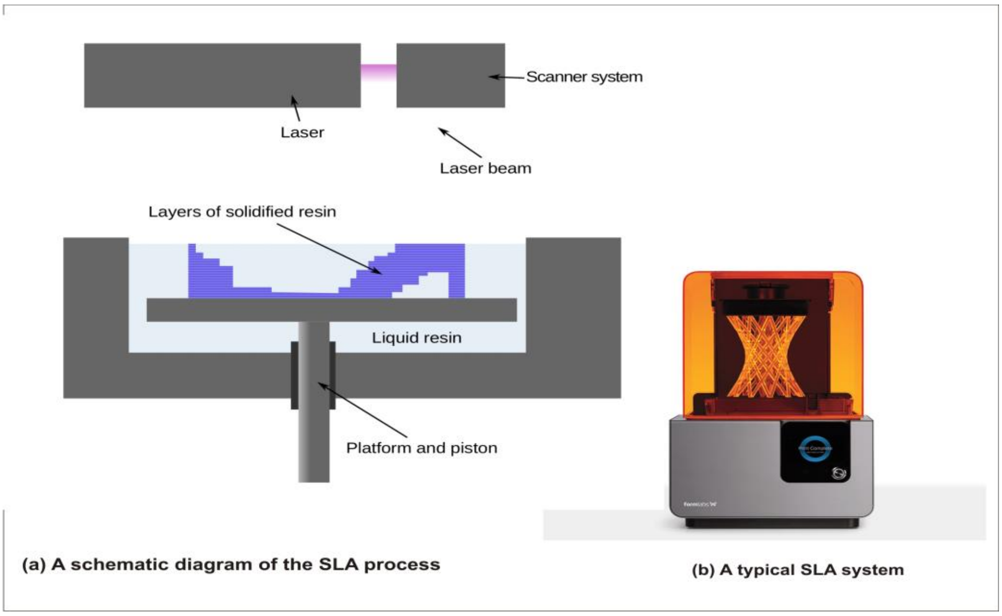


Figure 2. 8: Stereolithography (SLA) additive manufacturing technology. (**Source**: HS3DP, 2016)

- **Digital Light Processing (DLP)**

Digital Light Processing (DLP) is a technology developed in 1987 by Larry Hornbeck of Texas as instruments for multiple applications, and the applications include - projectors, spectroscopy, 3D scanners, machine vision, head-up displays and medical applications (Holtrup, 2015). According to Holtrup (2015) the technology is basically a matrix of millions of microscopic mirrors which have an angle that can be controlled from a Digital Micro-mirror Device (DMD) controller as shown in Figure 2.9 and it has a digital input from a microcontroller.

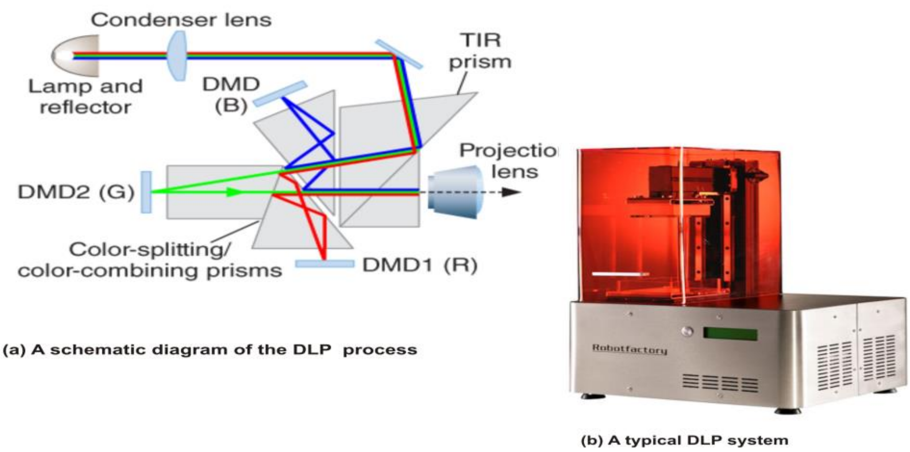


Figure 2. 9: Digital light processing AM technology. (**Source:** whiteclouds.com)

Digital light technology is used to print 3D object. Holtrup (2015) describes how digital light technology works and explained that “a thin layer of resin is cured by projecting an image on a photopolymer resin”. After a thin layer is cured, a stepper motor moves the layer one thicknesses upward or downward (to see the bottom-up & top-down section) and a new image is projected, and this process continues until a 3D product is made or formed. A 3D object printed through DLP technology is very robust and have excellent resolution.

Digital light processing has a very good advantage over Stereolithography because it uses less materials for detail production which results in lower cost and less waste (3DPS, 2015). The Envision Tec Ultra, MiiCraft High Resolution 3D printer, and Lunavast XG2 are good examples of DLP rinses (3DPS, 2015). Both digital light processing and Stereolithography works with photopolymers but they have different sources of light and moreover, DPL uses liquid plastic resin that is placed in the transparent resin container.

- **Fused Deposition Modelling (FDM)**

Fused Deposition Modelling is a widely used AM technology which was invented in late 1980s by Scott Crump, a co-founder and chairman of Stratasys Ltd; and Stratasys is a global leading manufacturer of AM machines and FDM was commercialized fully in 1990 (HS3DP, 2016). According to Zein *et al.* (2002) the FDM process forms a 3D object from a computer generated solid or surface model, that is, through a typical rapid prototyping process. The model can be designed from a computer tomography scans, magnetic resonance imaging scan or model data created from a 3D object digitizing system (Zein *et al.,* 2002). Zein *et al.* (2002) explain that "FDM technology uses a small temperature-controlled extruder to force out a thermoplastic filament material and deposit the semi-molten polymer onto a platform in a layer by layer process.

The monofilament is moved by two rollers and acts as a piston to drive the semi-molten extrudate and at the end of each finished layer, the base platform is lowered, and the next layer is deposited. The designed object is fabricated as a three-dimensional part based solely on the precise deposition of thin layer of the extrudate (Zein *et al.*, 2002). When comparing FDM method to other AM methods like Stereolithography (SLA) and Selective Laser Sintering (SLS); FDM method has a fairly slow process (LIVESCIENCE, 2013). FDM makes use of the following materials to printing 3D objects, such as - acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), and Polyetherimide. These materials are commonly thermoplastic. In addition, FDM uses water soluble wax or brittle thermoplastics such as Polyphenylsulfone for support materials (HS3DP, 2016). Figure 2.10 illustrates FDM processes with a typical FDM system.

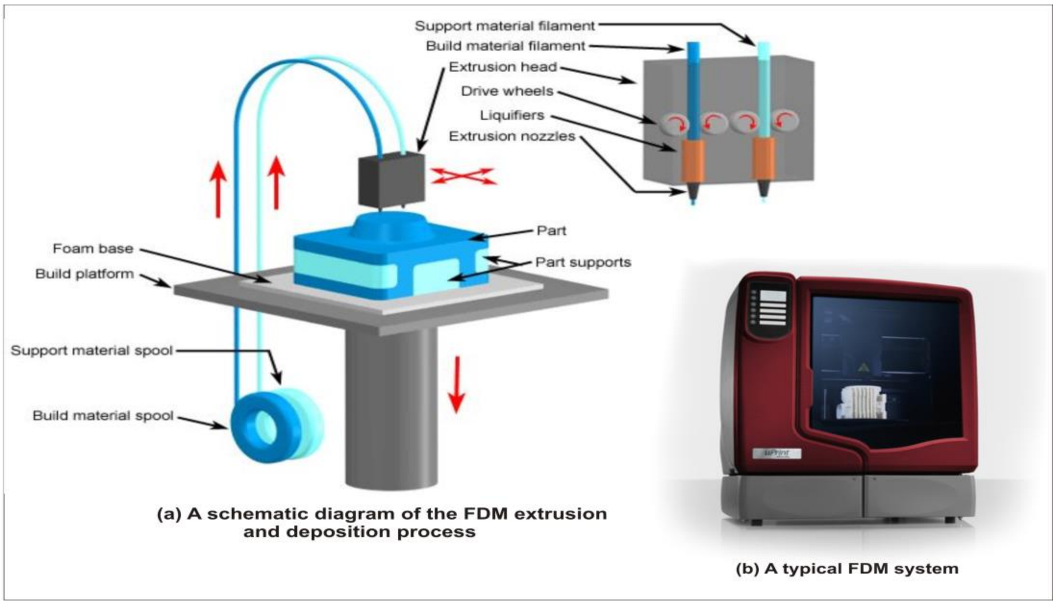


Figure 2. 10: Fused deposition modelling AM technology. (**Source:** CustomPartNet, 2008).

2.9.3 Additive manufacturing technologies – Sheet Lamination Methods

This addresses the sheet lamination method of AM technology; Laminated Object Manufacturing is discussed, and a schematic diagram is used to illustrate the technology.

- **Laminated Object Manufacturing (LOM)**

Laminated Object Manufacturing is not a widely used AM process, however, it is one of the most affordable and fastest AM machines. The cost of the printing is very low due to an inexpensive raw material use in LOM; and likewise, the printed objects from LOM can be big because no chemical reaction required to print large part (3DPS, 2015). LOM technology allows an object to be created by successively layering sheets of build material, bonding them through heat and pressure and then cut them into desired shape using either a blade or a carbon laser (Jermann, 2013). The object printed using LOM requires additional modification after printing using machining and drilling (HS3DP, 2016).

Jermann (2013) explains that LOM has a great advantage over other AM technologies because LOM materials are very consistent and readily available and well understood by many AM experts, but it depends on the type of binding resin used. LOM also provides one of the largest operating temperature windows as shown in Figure 2.11.

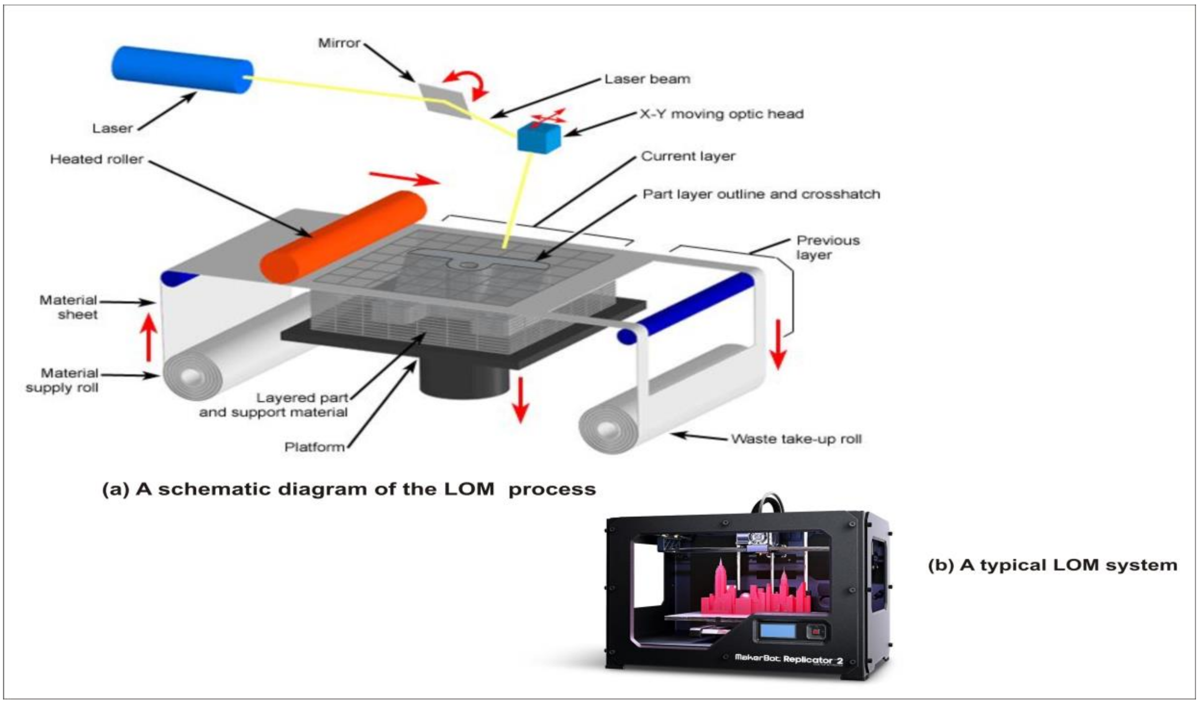


Figure 2. 11: Laminated Object Manufacturing AM technology. (**Source**: CustomPartNet, 2008)

Table 2.4 presents a quick summary of all the AM technologies and processes mentioned above.

Table 2. 4: Types of Additive Manufacturing Technologies (**Source:** HS3DP. 2016)

S/N	Method Type	Technology	Materials
1.	Extrusion	Fused Deposition Modelling (FDM)	Thermoplastics (e.g. PLA, ABS), HDPE, eutectic metals, Rubber, modelling clay, Plasticine, RTV silicone, porcelain, metal clay, etc.
2.	Wire	Electron Beam Freeform Fabrication (EBFF)	Almost any metal alloy
3.	Granular	Direct Metal Laser Sintering (DMLS)	Almost any metal alloy
		Electron Beam Melting (EBM)	Titanium alloys
		Selective Laser Melting (SLM)	Titanium alloys, Cobalt Chrome alloys, Stainless Steel, Aluminium.
		Selective Heat Sintering (SHS)	Thermoplastics
		Selective Laser Sintering (SLS)	Thermoplastics, metal powders, ceramic powders
4.	Powder Bed and Inject Head 3D Printing	Plaster-Based 3D Printing (PP)	Plaster

5.	Laminated	Laminated Object Manufacturing (LOM)	Paper, metal foil, plastic film
6.	Light polymerized	Stereolithography Apparatus (SLA)	Photopolymer
		Digital Light Processing (DLP)	Photopolymer

2.10 Chapter summary

This chapter has presented a general overview of additive manufacturing and identified various AM technologies and materials available. This chapter presents the history of AM and shown significant trends in AM industry since 1970s. This chapter reviewed the advantages, opportunities and challenges associated with AM and despite all the challenges and opportunities, there is a need for AM to grow beyond prototyping and move towards final product production. In this chapter has shown the huge investment of the South African government towards AM technology, research activities and educational development through the Department of Science and Technology and more so, this chapter have shown the South African AM journey, growth and development since 1991.

The next chapter presents the applications of AM/3D printing technology the context of university education. The next chapter reviews the recent studies on AM education from various scientific open access journals or publications, master dissertations and doctoral theses. The next chapter presents the existing framework for additive manufacturing technology. The chapter also reviewed the involvement of several universities in AM education worldwide and looks at the essence of AM/3D printing lab such as ‘Idea 2 Product lab’ at the universities and how it serves as good platform to introduce and promote AM education. Lastly, the chapter presents the use of entry-level FDM 3D printing machines as a tool for AM education.

Chapter 3

3. Additive Manufacturing/3D Printing Technology in Education

This chapter presents the literature review on the applications of additive manufacturing/3D printing in education with strict focus on university education. This chapter reviews various papers on the AM technology framework/implementation across different sectors; and previous studies as relating to AM education. This chapter also presents the use of AM/3D printing lab such as ‘Idea 2 Product (I2P) lab’ concepts as platform to integrate AM education at the university. More so, this chapter identifies the importance of entry-level FDM desktop 3D printing systems as a tool for AM education at the universities. This chapter also presents a SWOT analysis that evaluates both the present and future prospects of AM education and research at South African universities and lastly, the chapter ends with a summary.

3.1 Additive Manufacturing Education

The introduction of additive manufacturing/3D printing technology into the educational system is being referred to as ‘Additive Manufacturing Education (AME)’. Additive manufacturing education can be described as a vehicle through which additive manufacturing/3D printing technology is being introduced into the educational sector with the aim to promote and enhance the Science, Technology, Engineering and Mathematics (STEM) programmes at various educational levels, that is, from primary schools, high schools, colleges, universities and diverse industries. AM technology is relatively a new technology and still finding his way into the educational systems around the world. According to Schelly *et al.* (2015) additive manufacturing technology is rapidly revolutionizing the colleges, universities, and high schools, and bringing great possibilities to different educational disciplines ranging from Science, Technology, Engineering, Mathematics (STEM) and Geography, Geology, Biology, Chemistry, Industrial Design, Fine Art, etc. Therefore, for AM technology to reach its full potential, the educational aspect of this technology has to be properly integrated across different educational levels.

From a global perspective, the majority of the existing studies conducted in the field of AM focus more on specific and advanced research areas such as (quality of AM materials and final parts finishing, design topology and optimization, design for additive manufacturing, design and application of prosthetics in the medical sector, etc.) while only few studies centring on AM education and curriculum, or the development of a framework for AM education. More so, looking at AM education from a South African context, there are few established, or training programmes tailored towards the needs of AM industry in South Africa (Du Preez *et al.*, 2016).

As part of the plans of the Department of Science and Technology to integrate AM technology into South African educational system. In 2013, a stakeholder workshop was organized in South Africa, and education was highlighted as one of the main priorities to ensure successful adoption of the AM technology in South Africa (Du Preez *et al.* 2016). During the stakeholder workshop, some essential measures were identified to ensure AM education across different educational levels in South Africa, that is, from Primary/Secondary Schools, to Higher Education Institutions (HEI) and to diverse industries as listed below:

- To develop a short, medium and long-term educational framework for AM technology;
- To ensure school-level interventions to facilitate exposure to the AM technology;
- To provide widespread access to the AM technology at school level, for example through the establishment of computer labs and Computer Aided Design (CAD) software courses;
- To establish a national AM curriculum for all design and engineering schools at the HEI;
- To establish a dedicated bursary programme for both pre and post graduate studies in the field of AM/3D printing technology;
- To secure National Research Foundation and Department of Science and Technology Research Chairs for AM; and to establish a national AM centres at strategic locations.

3.2 Review of some studies on framework for Additive Manufacturing Technologies

Based on different literature reviewed on “framework for AM technology and education”, there are no specific framework that centres on AM education and this makes it difficult to find an existing framework for AM education to serve as a landscape to determine the new framework for AM education at the universities. Although, Go and Hart (2016) developed a curriculum framework for teaching basic additive manufacturing course at the university using Massachusetts Institute of Technology (MIT) as case study. However, the framework developed by Go and Hart (2016) is not framework for AM education at the university rather a framework for teaching the fundamental AM course at the university, which is just an aspect of the proposed framework for effective AM education - South African universities case study.

Furthermore, in order to develop an effective framework for AM education which very applicable to the university systems, it would be important to review some of the existing studies on “framework for additive manufacturing technologies/implementation/strategy” across different research areas and disciplines, such as areas include: mass customization, supply chain management, process monitoring and control, system engineering context, conceptual design, quality management, medical devices, industrial and product design as identified in these articles (Mellor, 2014; Handal, 2017; Deradjat and Minshall, 2015; Pradel *et al.,* 2018; Panesar *et al.*, 2015; Cummings *et al.,* 2017; Togwe *et al.*, 2018; and Williams *et al.*, 2011, Go and Hart, 2016).

As earlier stated in the first paragraph of this section that there is no existing framework for AM education at the university level that is found in literature as at the time of writing this doctoral thesis. However, majority of the existing framework for AM technologies reviewed in this section will be used to determine the educational strategy or serves as a landscape to determine/develop the newly proposed framework for AM education at the university in this thesis. The next paragraphs in this section presents an extensive review of the existing studies on framework for AM technology/implementation/strategy.

The first framework for additive manufacturing technologies to be considered is the Go and Hart (2016) study on the development of a framework for teaching basic AM course at the Massachusetts Institute of Technology (MIT) to enable rapid innovation. The framework presents an approach for teaching AM at both advanced undergraduate and graduate degree levels, the teaching method is in the form of 14-weeks AM course which provides the students with the opportunity to use entry-level 3D printers, i.e., desktop AM machines. The 14-weeks course includes a long-semester design build project which was developed and taught at the MIT. The adoption of AM education at MIT introduces a course in manufacturing to master's degree program and, also one-week professional short course program for industry engineers (Go and Hart, 2016). The framework developed by Go and Hart (2016) centres on the development of a curriculum for teaching AM course at the university and not framework for AM education at the university. However, their framework can be used as a strategy or landscape for other universities to build their AM educational courses.

Within the context of AM education, Swarup *et al* (2018) develop an innovative AM ecosystem training framework that is capable of accelerating the adoption of AM/3D printing technologies – a case study of Dayalbagh Educational Institute. The main objective of this AM ecosystem training framework is to encourage and enable students to build 3D printers and to increase the adoption rate for AM technologies within the educational institutions (Swarup *et al.*, 2018). This study proposed a framework that provides the students with potential opportunities to familiarize themselves with 3D printing production process and gain hands-on experience using open access technology, which is coupled with the understanding and application of relevant design skills (Swarup *et al.,* 2018). The teaching platform enables the students to understand how the entire systems are integrated, that is, software, 3D models, 3D printing system, 3D printing software and hardware.

From a global perspective, there are few engineering graduates with 3D printing knowledge and the approach adopted in this framework will provide engineering graduates with hands-on experience that allows them to turn their innovative ideas into reality (Swarup *et al.*, 2018). Swarup *et al.* (2018) study aims to "develop a sustainable and ubiquitous Learners, Users, Manufacturers, Innovators, Operators, and Serviceman (LUMINOS) ecosystem, suitable for educational forums and public spaces to facilitate and encourage action-based learning, exploration, and innovation, while accelerating the adoption of AM/3D printing technologies".

Furthermore, Mellor (2014) developed a 'framework for AM implementation' and, the study primarily focuses on the AM implementation process. The motivation for this study was based on the lack of socio-technical studies in AM research domain. The study addresses "the need for existing and potential future AM project managers to have an implementation framework to guide their efforts in adopting this new and potentially disruptive technology class to produce high value products and generate new business opportunities". Mellor (2014) proposes that the conceptual framework developed for AM implementation will be driven by external forces and internal strategies. Mellor (2014) believes that the approach of AM implementation would be controlled by five factors as shown in Figure 3.1. The five factors are listed below:

- Strategic Factors - [as AM Strategy]
- Technological Factors – [as AM Technology]
- Organizational Factors – [as Organization Changes]
- Operational Factors – [as System of Operation]
- Supply Chain Factors – [as AM Supply Chain]

As part of the recommendations for future work, Mellor (2014) and Mellor *et al.* (2013) suggests that the approach in their study can be compared and applied to different industry scenarios with other potential factors that could drive AM implementation framework and advises that this type of research can be tested or conducted using multiple case studies as this study was based on single case study. Mellor (2014) believes that as the number of implementers rises, different cases of AM implementation framework will be opened to researchers, and it is very difficult to conclude that there will be only one correct approach to AM processes or AM production implementation. Mellor (2014) study has provided a very good insight into various challenges with AM implementation processes and also, present a proposed conceptual AM framework that would help AM managers in implementing this novel and disruptive technology appropriately.

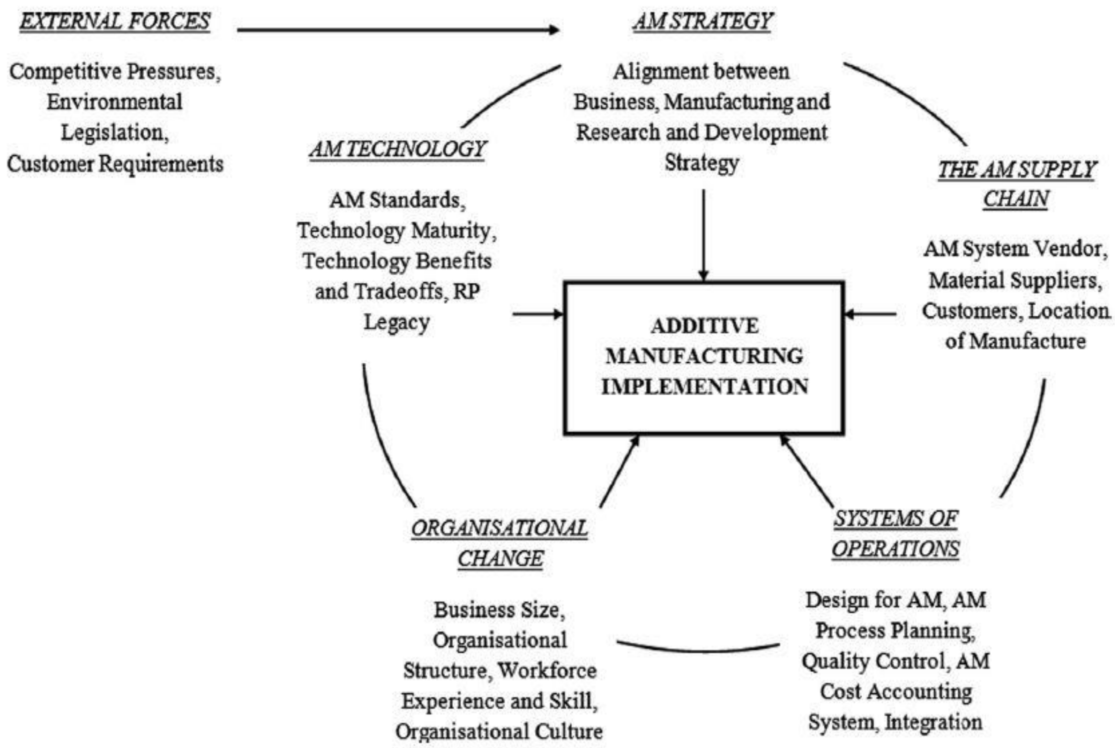


Figure 3 1: Proposed Framework for Additive Manufacturing Implementation

Source: Mellor *et al.* (2013) and Mellor (2014)

Deradjat and Minshall (2015) study identifies the limitation of Mellor (2014) proposed framework for AM implement, which contains five factors, namely: AM strategy, AM supply chain, system operations, organizational changes, and technological factors; and more so, the study used a single case study for its investigation. Deradjat and Minshall (2015) realized that there is a great potential for AM to influence Rapid Manufacturing (RM) and Mass Customization (MC). Deradjat and Minshall (2015) also identifies the gaps around the topic of mass customization using AM and a strong need to investigate how AM could facilitate mass customization since there are no existing studies on this topic.

Deradjat and Minshall's (2015) paper investigates how AM technology is being implemented by companies when it comes to mass customization of products from technical, economic and business management perspectives. Their study also makes a significant contribution to the literature gaps in the research areas of RM, MC and Advanced Manufacturing Technologies (AMT) implementation frameworks. Based on different literature review, Deradjat and Minshall (2015) considered four factors that could influence AM implementation for mass customization, and these factors are divided into: 1. Technological factors; 2. Operational factors; 3. Organization factors and 4. Internal/External factors as shown in Figure 3.2.

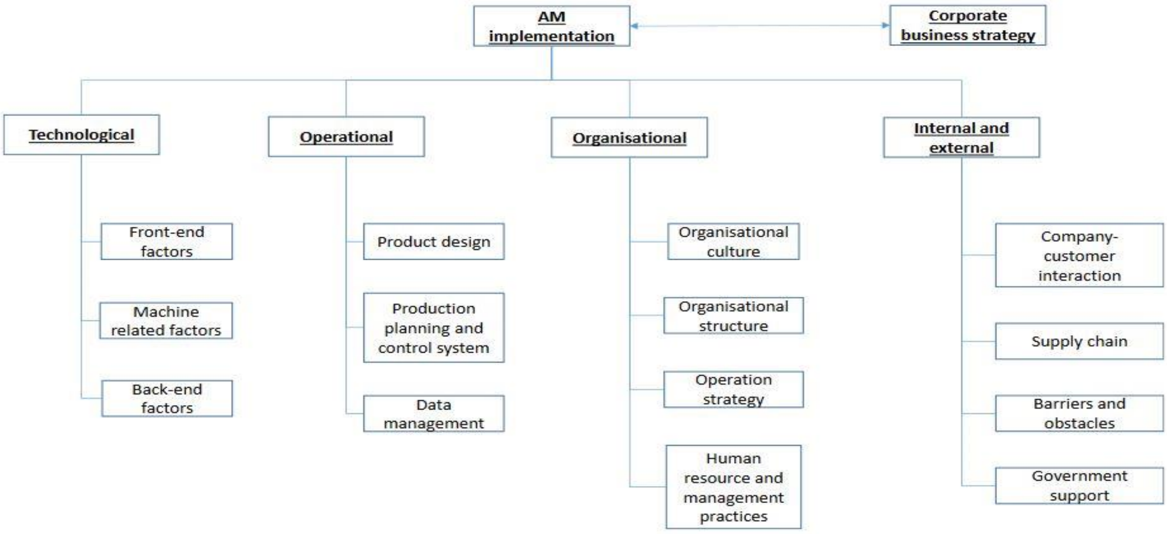


Figure 3 2: Framework for Additive Manufacturing Implementation for Mass Customization

Source: Deradjat and Minshall (2015)

The framework was developed primarily to determine the significance of different factors that influences the implementation of AM for mass customization (Deradjat and Minshall, 2015). The study provides relevant insights into more case studies or research areas to be investigated in the future such as medical, dental, surgical implants, etc. through the development of an implementation framework (Deradjat and Minshall, 2015).

Further research work was carried out by Deradjat and Minshall (2017) considering the shortcomings of identified in Deradjat and Minshall (2015) and Mellor (2014) studies. Firstly, Mellor (2014) study was very generalized and does not contain the technological factors, for example, post-processing and needed software component; and variables can change during implementation processes while Deradjat and Minshall (2015) study emphases on the significance of technological factors and the study does not accommodate the implementation process stages and portray all factors as independent variables not as interdependence variables/factors. As a result of this, Deradjat and Minshall (2017) recognises the shortcomings of these previous studies and further extends their study further by proposing a framework for RM implementation of MC using the dental industry as a case study. The dental industry was chosen as the case study because the dental industry is currently recognized as one of the major users of AM technologies.

This study addresses the gaps in literature around mass customization through rapid manufacturing and provide further insights on the way organizations implement RM for MC in the dental industry. To achieve the overall objective of the study, one research question "*How do* *companies implement RM for MC in the dental industry*" was answered effectively and a framework for rapid manufacturing implementation for mass customization in the dental industry was developed using five interdependence factors/variables, that is, [corporate strategy, technological, operational, organizational, external factors] as presented in Figure 3.3 (Deradjat and Minshall, 2017).

Figure 3 3: Framework for Rapid Manufacturing implementation for Mass Customization in Dental Industry

Source: Deradjat and Minshall (2017)

Deradjat and Minshall (2017) includes the implementation phases in the study, which was divided into three phases: pre-installation, installation and commissioning and post-commissioning phases. Each of the factor in the framework is characterized by sub-factors that support it, for instance, external factor has - customer requirements, competitive pressure, collaboration, and regulation as sub-factors. The findings from the study shows how RM implementation for MC requires diverse consideration based on the phase of implementation and the maturity level of the technologies involved. The study identifies 26 challenges that seem to play a significant role in the implementation processes (Deradjat and Minshall, 2017).

Moreover, this study considers the healthcare sector but from a quality management perspective, Yeong and Chua (2013) developed a quality management framework for implementing AM for medical devices. The proposed framework used certain factors such as input data, process understanding, material management, product understanding, equipment qualification for AM, etc. as shown in Figure 3.4. The framework also shows the interrelations between the factors from input material to final production of AM parts. It believes that the framework will accelerate and ease the adoption rate of AM technologies as actual manufacturing method.

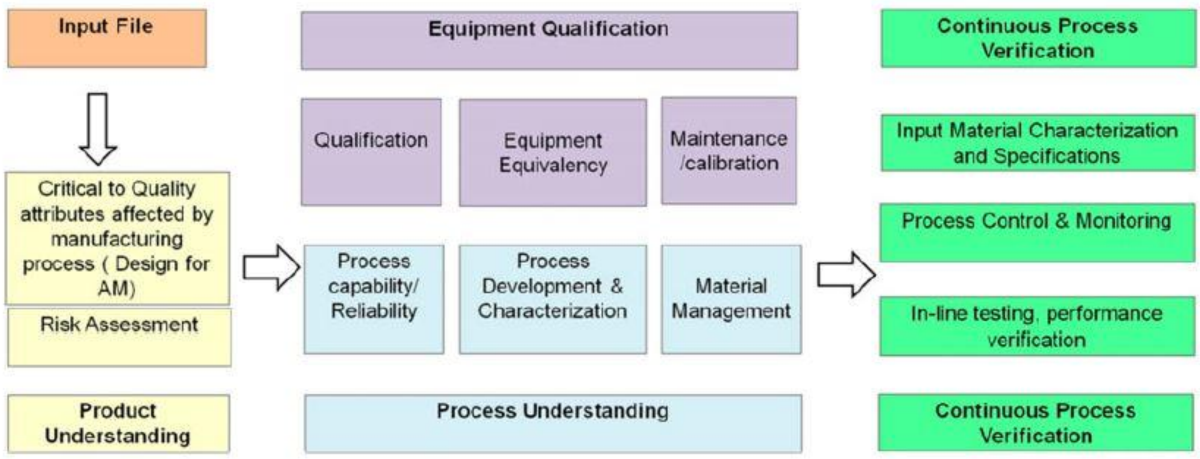


Figure 3 4: A Quality Management Framework for Additive Manufacturing for Medical Devices

Source: Yeong and Chua (2013)

In another study from a supply chain perspective, a conceptual framework for AM implementation in Supply Chain Management (SCM) was developed (Handal, 2017). It was observed that many popular management practices within the production sector will change if there is a full implementation of AM technology. More so, there are little literature in the research domain of AM that shows its impact on SCM and there is no complete toolset identified in manufacturing sector that can be used to assess the impact of AM. As a result of this, Handal (2017) study aims to develop an effective framework to describe when AM impacts SCM and the framework was developed based on theories received through extensive literature reviews (Walter *et al.*, 2004; Tuck and Hague, 2006; Ruffo *et al.*, 2006).

The conceptual framework consists of three main factors - manufacturing strategy (customization, product type, component value); supply chain strategy (lean supply chain strategy and agile supply chain strategy), and manufacturing system (additive manufacturing, hybrid manufacturing, and traditional manufacturing) as shown in Figure 3.5 (Handal, 2017). Secondly, a theoretical framework was developed also which was based on fisher (1997) framework. Fisher's (1997) framework suggests two supply chain strategies fundamental, namely, 1.) efficiency in production strategy which is characterized by (end-end optimization, short-time to market, and continuous production) and responsiveness to market strategy which is also being characterized by (agility, flexibility, and customization). The outcomes from this study show that the theoretical framework indicates that AM can be implemented if the company is adopting either efficiency in production or responsiveness to market supply chain strategies (Handal, 2017).

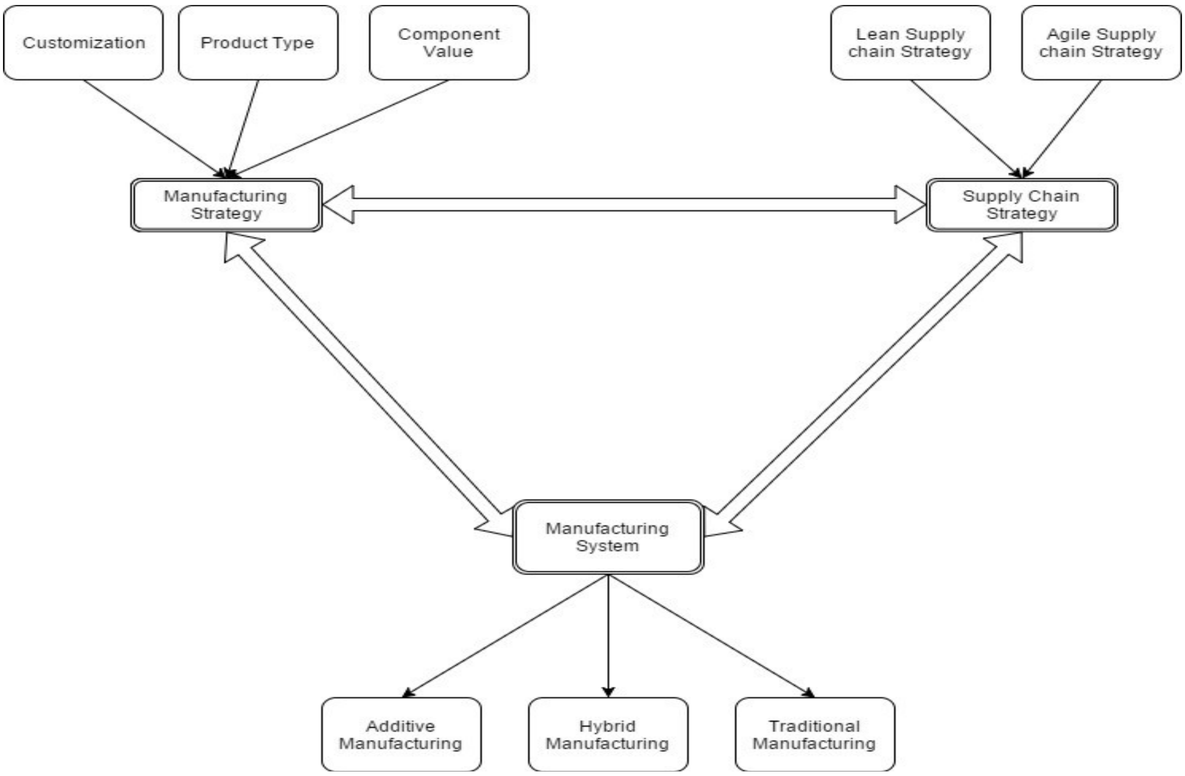


Figure 3 5: Conceptual framework for Additive Manufacturing Implementation in SCM.

Source: Handal (2017)

Recently, Pradel *et al.* (2018) conduct a research on "a framework for mapping design for additive manufacturing knowledge for industrial and product design" collates and organizes the research field of Design for Additive Manufacturing (DfAM) knowledge through single and well-organized conceptual framework. According to Pradel *et al.* (2018) eighty-one different publications on DfAM were put together to make up the framework which clearly summarizes the state-of-the-art across the entire design processes for the very first time. The framework consists of five parts/factors, namely: 1. Conceptual design; 2. Embodiment design; 3. Detail design; 4. Process planning; and 5. Process selection, which were based on generic design process. The study also proposed future areas of research for DfAM such as generic materials in AM, AM process selection and topology optimization. (Pradel *et al.*, 2018).

As earlier stated, most of the existing framework developed in the research domain of AM technology are not directly tailored toward AM education. However, majority of framework for AM technology reviewed and presented in this section provides fundamental insight for the researcher and serves as a landscape for the researcher to determine the strategy for the development of a framework for AM education of this thesis.

3.3 Recent studies on Additive Manufacturing/3D printing education

There are so many studies conducted within the engineering education context, but few studies were conducted directly related to AM education and this might be as a result of the infancy stage of AM technology. However, in recent times, few studies were specifically tailored toward AM education within the university systems. Therefore, in this section, some recent studies on AM education from an engineering perspective were presented.

At the University of Texas, additive manufacturing education was introduced into the education system through the design of a course “Design for Additive Manufacturing” for both undergraduate and postgraduate AM courses. The teaching approach is based on Project-based and Project based approaches which gives the students the opportunity to acquire hand-on experience using AM technology (Williams and Seepersad, 2012). The general class structures for the AM curriculum includes the following topics: Identifying AM opportunities, History of AM, AM project planning and economic, AM concepts generation, AM embodiment design, and AM detailed design. Introduction of this AM curriculum has greatly helped the students in applying their newly-acquired knowledge of design for additive manufacturing to carry out their final project through the whole product development process from the creative idea to AM technology and to final testing (Williams and Seepersad, 2012).

A study by Minetola *et al.* (2015) entitled “impact of additive manufacturing on engineering education – evidence from Italy”. This study aimed at evaluating the way direct access to additive manufacturing machines could impact future mechanical engineering education using MSc program in Mechanical Engineering – a case study of the Polytechnic University of Turin in Italy. The Polytechnic University of Turin is a top Italian university, a partly public engineering university (Minetola *et al.*, 2015). This study used quantitative research methodology, that is ‘a questionnaire survey’ which contains both closed and open - ended questions. The questionnaire was designed specifically to evaluate the relevance of an entry-level AM machines i.e. desktop FDM 3D printers within the learning environment and as a tool for project development (Minetola *et al.*, 2015).

The survey was administered to three consecutive groups of students anonymously who attend “computer-aided production, CAP” courses within the postgraduate degree programmes in Mechanical Engineering (i.e. Master of Science degree). The CAP course consists of a practical project that allows the students to design, fabricate, assemble prototype, final part and etc. The survey focuses on the learning processes of the practical project which includes - motivation, interest, team working, impact, geometry, assembly, functionality, process, education, lab practice and modification. The research finding stated that “there is a positive relationship of access to AM systems to perceive interest, motivation and ease of learning of mechanical engineering”. The research findings show that entry-level FDM AM technology provides students and lecturers with hands-on-experience and thereby, promoting technical knowledge acquisition and early exposure of students to AM tools would make them have a “think additive” mind set to product design and development (Minetola *et al.*, 2015).

Gatto *et al.* (2015) conducted a multi-disciplinary research with the focus on engineering education, that is, an approach into learning with AM and reverse engineering. The research was conducted at an Italian university called *University of Modena and Reggio Emilia.* The study is a ‘cooperative-learning project’ of a second-year course within a MSc degree program in Mechanical Engineering as the case study. The aim of this study was to “create awareness of the educational impact of AM and reverse engineering”. To achieve the aim of this study, the students were asked to develop a design and manufacturing solution for an eye-tracker head mount concurrently using AM techniques and the eye-tracker head model was reverse engineered. The practical project required the students to test the prototype, perform cost analysis and evaluate. The research findings show that the study supports the “authors’ belief in the tremendous potential of interdisciplinary project-based learning, relying on innovative technologies to encourage collaboration, motivation and dynamism”.

Schelly *et al.* (2015) carried a study on the use of open-source 3D printing technologies for educational purposes. The main aim of the study is to “investigate the potential of open source technologies in an educational setting, given the combination of economic constraints affecting all education environments and the ability of open-source design to profoundly decrease the cost of technological tools and technological innovation”. The research employed a 3-day workshop with 22 teachers (i.e. middle and high school level educators) across various disciplines participated. During the workshop, online instructional and visual tools were used, which were primarily designed for middle and high school teachers (Schelly *et al.*, 2015).

The 3-day workshop was carefully observed for evaluation and research; and focus group methodology was used where the teachers were grouped into 2. The focus group enables each educator to discuss their interest in open-source AM/3D printing technology and how it has impacted their classrooms and each teacher completed a voluntary open-ended survey question after the 3-day workshop (Schelly *et al.*, 2015). The teachers were able to build 3D printers using open-source technologies during the workshop and the 3D printers were taken back to into their school and classroom. Schelly *et al.* (2015) findings show that open-source AM/3D printing technologies have a great capability to enhance the educational sector with a sense of empowerment emanating through cross-curriculum engagement and active participation of the teachers and students.

A study was conducted by Colletti (2016) with strong aim to determine the positions available and the educational levels and skills required to be successfully working in the field of AM and to identify the types of companies that required AM expertise within their workforce (i.e. the engineers) and the company locations. The research methodology/design used in this study was a "*mixed-methods*" which involved two content analyses. The first part of the study analysed 286 position descriptions collected from 5 search engines basically designed for job purposes, while the second part of study was based on the analysis of the information available on AM education and training programs. The third approach in the study involved the use of a questionnaire which was circulated among 2000 members of AM Users Group and 1000 attendees of a yearly conference on AM organized by the Society of Manufacturing Engineers. The collected data were analysed using descriptive statistical tools. The results from the study shows that AM technology is playing an important role from business strategy perspective, companies' culture and organization structures of organizations (Colletti, 2016).

Furthermore, the research findings show that "the highest degree needed for the position of manufacturing engineer within AM industry is a bachelor's degree while a non-specific engineering degree will require one to five years working experience. More so, the outcomes of the study show that in AM industry, the manufacturing and tooling industry is in high demand for trained and experience AM experts (Colletti, 2016). Colletti (2016) suggests that colleges and universities should assist in developing training programmes and short course certificates that teach new advancements in AM technologies in collaboration with industry and professional engineers in various organizations. Colletti's (2016) findings can be used as baseline for colleges and universities in the development of AM curriculum, certification courses, and training for students, academics and professionals in industry; also, the results of the study can be used by companies in collaboration academia in talent and workforce development in the field of AM. However, the findings in this study show that AM education and skill developments are still lacking within the manufacturing workforce (Colletti, 2016).

Serdar's (2016) study addresses the educational challenges involved in design for AM. The study suggested that students need to learn how to design for both complex and customized parts for the future uses of AM. Additive manufacturing long-term success depends on the ability of the designers or STEM workforce that can think conceptually different compared to the conventional ways. At the University of Pittsburgh, MET1172 – CADD/CAE is Design Project for AM course and the "MET1172 – CADD/CAE course" assignment was modified to assist students' visualization and improve students' design skills with complex geometries using AM technology for products development and manufacturing (Serdar, 2016). More requirements were added to MET1172 course project that allows the students to design from an AM technology point of view and such approach is called "Inquire-based learning activities" i.e. the ability of the students to '*learn by doing'* (Serdar, 2016). The study also addressed various challenges that students encountered during designing for AM; such challenges identified includes are - 1. the ability of the student to visualize complex geometries; and 2. designing using complex Computer Aided Design features. Lastly, the class evaluates the MET1172 projects and it was indicated that the project aspect made a valuable contribution to students' learning experience (Serdar, 2016).

Harvey (2016) study entitled "Teaching Additive Manufacturing in a Higher Education Setting; - a case study of University of Wollongong. A course was introduced to the final year program called 'MECH 482- Introduction to Additive Manufacturing' and the course comprises of lectures, tutorial, lab work, group discussion, site visit to AM research and production facilities. The program delivery included Project-Based Learning (PjBL) method (Williams and Seepersad, 2012; Harvey, 2016). MECH 482 is introduced to provide a solid academic foundation and hands-on-experience to students within the field of AM. The study evaluates the effectiveness of teaching AM to final year engineering students at the university using project-based learning approach. The university established an 'AM laboratory' which is well-equipped with seven 3D printers for the use of students. The students were able to build new learning skills in Computer-Aided Design (CAD) and related 'soft skills', for instance, project management, quality assurance, etc. (Harvey, 2016).

The key measurable results of the study were obtained from the faculty result sets and students' subject evaluation. The feedback from the students' subject evaluation indicated that the students responded very positively to different mediums of teaching used by the lecturers and the students' feedback shows that they benefited from applying the theoretical knowledge of AM which allows them to build quality physical models for the project aspect of the course. However, due to the high pass rates in the MECH 482 course, students indicated that the subject difficulty and academic content of the course were set too low for a final year course and as a result of this, the course content was increased to meet the level of academic rigour and to a more acceptable standard to suit a final-year degree course/subject (Harvey, 2016). The study concluded that the MECH 482 course identified to be the most commonly choice for final year students and many of their graduates are currently being employed in the AM sector.

Waseem *et al.* (2016) study on AM education entitled “Innovation in Education - Inclusion of 3D-Printing Technology in Modern Education System of Pakistan: Case from Pakistani Educational Institutes”. The primary aim of this study was “to examine and shed light over current education system of Pakistan without opting modern 3D printing technology in the classroom learning and how it can be beneficial for educational purposes”. Their study analysed the Pakistan traditional education system when compared to the international present-day education system with AM/3D printing technology, and the way this technology has revolutionized today educational systems (Waseem *et al.*, 2016). This study uses qualitative research methodology i.e. semi-structured interviews with small sample size of (n=7) to seek the understanding and perspective of students, lecturers/teachers, and the 3D printing service providers on their perception on the inclusion of AM technology into the Pakistani education system.

Furthermore, the data were collected and analysed using a content analysis method and applied verbatim texts in discussing the emergent factors/themes. The study findings show that the students and lecturers/teachers believed and convinced that AM/3D printing technology would revolutionize the Pakistan educational system in the future, the same way computers did. Waseem *et al.* (2016) believes that AM technology rely so much on modern-day learning techniques in presenting innovative ideas in a tangible manner, and based on their current practices, the study suggested that primary and basic education systems should embrace AM technology to create a better environment for innovative thinkers. Due to small sample sizes used in this study, generalization of the findings is very limited, and the authors make suggestions that future research should use larger sample sizes for generalization purposes.

Waseem *et al.* (2016) recommend that engineering, and technology universities will greatly transform innovative ideas into reality if they have or acquire AM/3D printers *as in-house facilities at their faculty/universities with well-equipped faculty AM experts and trained AM specialist*. In conclusion, Waseem *et al.* (2016) stresses that the establishment of 3D printing laboratory in the universities/institutes will go a long way in introducing AM education at the universities worldwide. The findings from this study is very useful and extensive for the higher educational institutions, researchers, students, industries and the society at large.

Despeisse and Minshall's (2017) recent publication titled "skills and education for AM: a review of emerging issues"; the study addresses the present talent shortage needed to deliver necessary skills and knowledge for an effective deployment of AM technologies. The publication presents some key matters or issues in the education environment needed to address the current skills gap and barriers in adopting and exploiting AM technology (Despeisse and Minshall, 2017). This study was based on literature reviews and evidence collected through different stakeholder workshops. According to Despeisse and Minshall (2017), the study was carried out "as part of the 'bit by bit' project and the activities leading to the development of the UK National Strategy for Additive Manufacturing" (Minshall and Dickens, 2015).

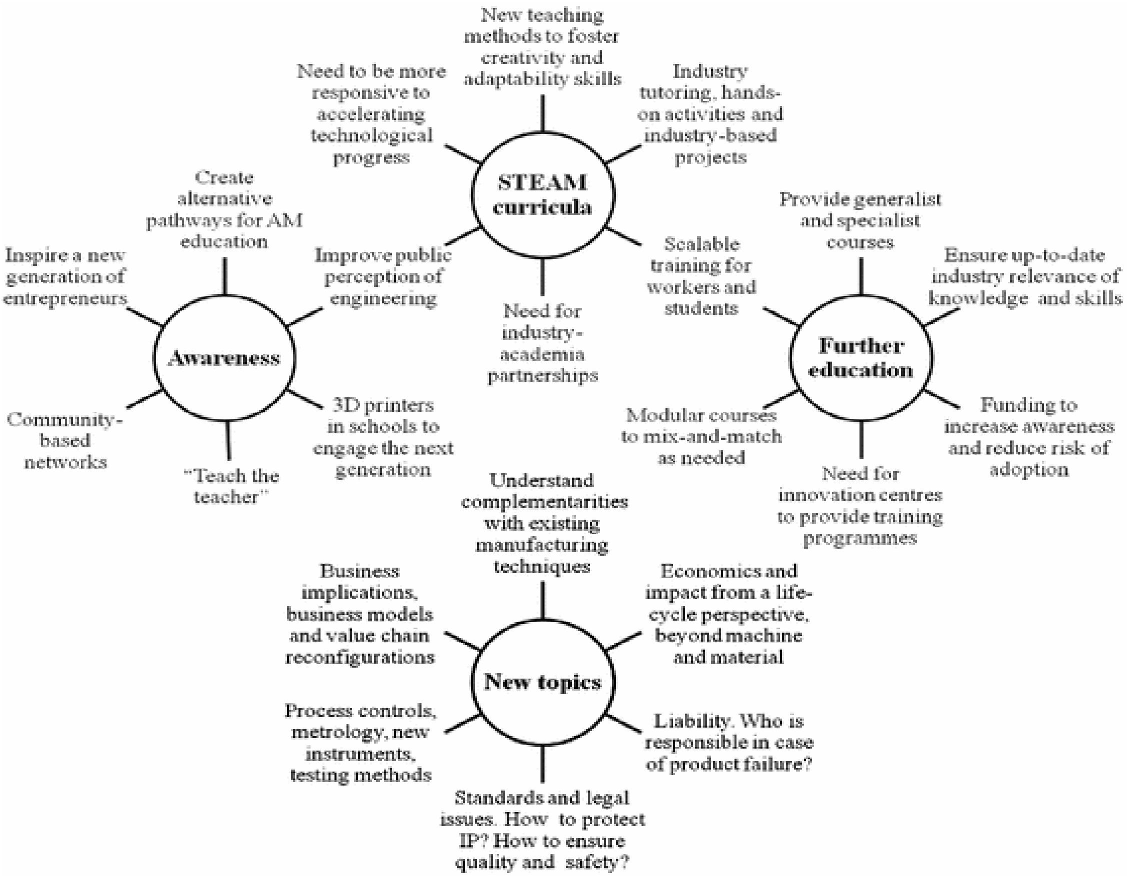


Figure 3 6: The Mind-map of recommendations for AM education and training; and its associated issues

Source: Despeisse and Minshall (2017).

Despeisse and Minshall's (2017) study identify key issues and barriers perceived hindering the adoption and exploitation of AM and the study reviewed the current educational and training program in AM for both undergraduate and postgraduate courses ranging from full academic program to short courses or modules for professionals in industry (Despeisse and Minshall, 2017). The paper summarises some basic skills for AM and recommendations were made for

AM education program to enhance the AM skills for students, lectures, designers, engineers and managers in industries (Despeisse and Minshall, 2017).

Based on common AM barriers identified such as lack of specific design skills, uncertainties in part qualification, lack of standard in production and limited materials to work with. Despeisse and Minshall (2017) stated that there is a strong need to effectively educate future engineers on AM technologies as many engineering students both at the university and industry are not familiar with AM technologies and this is recognized as a crucial barrier for industrial adoption of AM technology. Despeisse and Minshall (2017) concludes their study with a mind-map representation with the main issues poorly placed at the centre in bold letters and recommendations for AM education and training arranged around the issues/barriers as shown in Figure 3.6.

Drakoulaki (2017) study entitled "3D printing as learning activity in the higher education - a case study of a robotics prototyping course" at the University of Oslo, Norway. The study focuses on the learning aspect of AM education among higher education students. The study addresses the problem of "how 3D printing may support learning and knowledge construction in the university and how this activity relates to students". Furthermore, Drakoulaki (2017) study explores the research question of "how 3D printing technology does serve as a tool for learning and also how do the lecturers and students perceive the significance of the 3D printing for learning purpose at the university". The research findings show how students take part in different types of knowledge practices during the AM process, such as redesigning, visualizing, designing and printing. The analysis also shows how the 3D printing process gives the students the privilege to assemble and work of several knowledge forms and representation. Hence, the study identifies the challenges in the learning process using AM systems, such challenges are: knowing the different between AM technology and what the artefacts can be offered during the entire processes (Drakoulaki, 2017).

Conclusively, Radharamanan's (2017) study on "AM in manufacturing education, implementation and development of a new course at the Mercer University. The study shows the significance of incorporating AM into the manufacturing curriculum of the engineering education; a senior level AM elective course was developed to provide students taking the AM elective course with hands-on experience. In the course, the students learnt the fundamental AM processes and they were also trained using different design tools like (123D Design, Pro E and Netfabb). The students used 3D printers and printed parts and different materials such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). To enhance the student learning during the course, an affordable or low-cost AM machine was set up in the rapid prototyping (RP) laboratory on campus which consists of CAD software, 3D scanners, 3D printers, CNC mill and digital measuring tools (Radharamanan, 2017).

As part of the web resources used in the theory classes, YouTube videos on AM processes and applications were extensively used to expose the students to new ways of teaching. The course curriculum for the senior level AM elective includes the following “basic principles of AM, difference between traditional manufacturing processes (subtractive manufacturing) and AM, recent advances in the AM technologies that specializes in rapid prototyping of three-dimensional objects such as photopolymerization, powder bed fusion, extrusion, beam deposition, sheet lamination, direct write technologies, and direct digital manufacturing; design for AM, process selection, postprocessing, software issues, rapid tooling, applications of AM, business opportunities, and future of AM” (Radharamanan, 2017).

3.4 Recent global advances in Additive Manufacturing education at the universities

Different journal articles have shown tremendous involvements of different organizations such as (General Electric Additive Education Programme, research institutes, corporate initiatives); and universities across (Europe, Asia, United Kingdom, Canada, United States of America and Africa) in AM education through the integration and implementation of AM courses, introduction of postgraduate degree programmes, and the establishment of AM laboratories with such name as (AM Lab, 3D printing lab/centre, Idea 2 Product lab, AM teaching factory, and etc.). In this section, recent advances in AM education across different universities and organizations are presented.

Dickens *et al.* (2016) paper on AM education in the United Kingdom shows the journey of AM education in the United Kingdom. The paper stated that AM education started in the United Kingdom in March 1992 with a seminar organized by the institution of Mechanical Engineers coupled with an industrial exhibition stand. The research paper also mentioned that United Kingdom has Additive Manufacturing Research Landscape that includes educational activities and organization involvement. First AM/rapid prototyping conference in Europe was held at the University of Nottingham in 1992. As at 2012, 81 organizations across United Kingdom were identified previously or currently engage in AM research activities since 2007, and out of the 81 organizations, 24 are universities and 57 are companies with 151 AM machines. Between 2007 and 2016, the United Kingdom government has invested £95.6-million on AM research and Technology Transfer across UK and in industrial AM research and development (R&D), £20.5

million has been given to industry & universities altogether (Dickens *et al.*, 2016). In conclusion, the paper contains a comprehensive review of various activities of AM in the United Kingdom.

According to Go and Hart (2016), as at 2009, AM education was identified as a critical area in the advancement of AM field, and the introduction of AM programs at the universities, industries, and technical colleges, management organization and the public is very important. As a result of this, many AM educational initiatives and programmes have been launched worldwide and universities in the United States such as (Massachusetts Institute of Technology, Pennsylvania State University, Missouri University of Science and Technology, University of Tennessee, University of Louisville, University of Texas, Deloitte University, etc.) have embraced and integrated AM education activities at both undergraduate and postgraduate levels, most especially in the engineering educational curriculum. For instance, Pennsylvania state university commonly known as ‘Penn State University’, college of engineering has recently introduced a master’s degrees in “Additive Manufacturing and Design” for fall 2017, which is in response to increased industry demand for more experts and professionals in the rapidly growing field of AM technologies in the United States (Pennstate, 2017).

In the same vein, some universities in the United Kingdom (such as Loughborough University, University of Nottingham - EPSRC Centre for Doctoral Training in Additive Manufacturing and 3D printing, University of Sheffield, Newcastle University, University of Liverpool, etc.) are strongly involved in AM research. More so, some universities in China such as (Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, and South China University of Technology) have integrated AM education into their educational curriculum (Dickens *et al.*, 2016; Lin *et al.*, 2012 and Hague *et al.*, 2016, Go and Hart, 2016).

As additive manufacturing technology advances into the university educational systems and manufacturing industries. Introduction of postgraduate programmes is very crucial at this stage and different universities have started introducing MSc programme in additive manufacturing in order to enhance additive manufacturing education and increase industry engineers and professionals in the field of AM, and such universities include: Colorado State University who has introduced a 'MECH 502 - Advanced/Additive Manufacturing Engineering' as part of the courses to be undertaken during master programme in mechanical engineering in 2016 (CSU, 2016). University of Sheffield, UK, started a Master’s degree program by research [MSc (Res)] in Additive Manufacturing and Advanced Manufacturing Technologies within the Department of Mechanical Engineering (UOS, 2016). In 2018, Derby University in the United Kingdom is starting a Master of Science (MSc Advanced materials and Additive Manufacturing). Also, Loughborough University is starting an MSc in Design for Additive Manufacture in 2019 with the aim to cover key areas such as digital design and fabrication (Loughborough, 2018).

Gradually, additive manufacturing education has drawn the attention of various industries and universities across the world; and this has led to much collaboration between the universities and industries, for instance, in 2017, the engineering giant (General Electric) has committed $10 million over the next five years to school and college programmes in the United State to develop future talent in AM/3D printing/production technologies through AM education. GE additive believes that "enabling educational institutions to provide access to 3D printers will help accelerate the adoption of AM, worldwide" and this collaboration is to further strengthen GE position in rapidly growing markets of AM (Optics, 2017).

Auburn University in the United State has recently embraced AM education and have developed "Auburn University's Roadmap to Additive Manufacturing Education". In June 2016, the university announced the establishment of a new 'Centre for Industrial Additive Manufacturing' as part of General Electric Additive Education program and Auburn university was among the eight universities selected worldwide by GE). General Electric provided the university with Concept Lazer MLab 100R metal printers in addition to the two metal additive manufacturing machines (i.e. Renishaw Am 250 and EOS M290) already owned by Auburn university. More so, the university has started offering a Certificate in Additive Manufacturing in mechanical engineering with course titled: 'MECH-5970' (Donaldson, 2018).

Similarly, as part of industries collaboration on AM education programme. In 2017, two United States-based companies announced a training collaboration to focus on AM education. The purpose of the collaboration is to promote the proper usage and advances of AM technologies, and to drive AM knowledge into the manufacturing sector faster and more consistently. Their training curriculum includes foundational level learning and more complex design, material, process, business and quality and safety courses in AM (PRNewswire, 2017).

In 2016, National Forum on Additive Manufacturing Education and Training organized a forum at the Penn State University, which brought many educators and industry in AM together in order to address the need for engineering education to adapt to AM technologies. The forum explored the question "how should engineering and manufacturing education adapt to the advance of AM?" (Zelinski, 2016). The outcomes of the conference show that there is a need for science, technology, engineering and mathematics (STEM) educators, university academics/researchers and industries to collectively adapt or develop education strategies to prepare students for 21st century STEM manufacturing techniques such as additive manufacturing (ITEEA, 2016).

Thurn *et al.* (2017) approach AM education for teaching and promoting innovations using a mobile 3D printing lab known as “rolling laboratory”. The rolling bus laboratory was initiated with the aim to integrate the rural and under-industrialized parts of the nation into the high-technology education system. To achieve this, there is a need for professional training for learners from high schools to the universities and professional staffs across industries. To reach people within these categories, a mobile 3D printing strategy was born based on this old proverb “If the mountain won't come to the prophet, the prophet must go to the mountain” (Thurn *et al.* 2017). The mobile 3D printing is called “FabBus 3D Printing Inside” which uses a redesigned double-decker which comprises of technical infrastructure and educational tools that makes it easier to teach a short-term AM course. The primary aim of developing a mobile 3D printing laboratory facility was to enable flexible use of 3D printers in the schools, educational institutions and companies. The first floor of the bus consists of eight computer spaces that contains all the relevant softwares such as CAD, 3D printers, simulation tools and software for printing as shown in Figure 3.7.

Figure 3 7: The rolling laboratory concept, mobile 3D printing lab.

(a) the re-designed double decker bus called 3D printing inside (b) and (c) shows the first floor of the bus as the teaching area while the ground floor is the show room and the industrial area. **Source:** Thurn *et al.* (2017)

The rolling laboratory was inaugurated in May 2015 and the mobile 3D printing laboratory touring Germany's border and neighbouring countries such as Belgium and the Netherlands. The study shows that different target groups show interest in this initiative. According to Thurn *et al.* (2017) between May 2015 and December 2016, above 50 missions and target groups were covered such as schools, universities, small and medium-sized enterprises/companies, trade groups and etc. The application areas of AM are very broad and since the inception of the rolling laboratory, several industries show interest in AM training and education. In order to meet the needs of different target groups, Thurn *et al.* (2017) developed a new AM teaching concept that allows each target groups to be equipped with both theoretical and practical knowledge of AM education within a week. The use of mobile 3D printing laboratory can assist in addressing the challenging issues of training and educating students and professionals in the field of AM.

3.5 Problem-Based Learning Approach to Additive Manufacturing Education

In Problem-Base Learning techniques, "the students are expected to go through an extended process of inquiry in response to a design question, a problem, or a challenge that usually requires more than an individual effort to handle and overcome" (Zancul *et al*, 2017; Chua et al., 2014). Implementation of problem-based learning approach could be very difficult, but its application using Additive Manufacturing/3D printing technologies can make it easier to implement, especially within the engineering education curriculum. Recently, Project-Based Learning (PBL) approach have been discussed across different literature and it is referred to as one of the most effective teaching frameworks for engineering education (Zancul *et al*, 2017).

Tang and Mo (2015) also referred to Problem-based learning approach as a team-based teaching and learning technique that employs "real life" problem to assist students in gaining both technical knowledge and necessary skill sets for problem-solving, research, effective communication and collaborative engagements. PBL generally provides student with real life situation and expected to proposed solutions that would assist to optimise the situation. For instance, Tang and Mo (2015) study proposed a Problem-based learning approach to teach students Systems Engineering using Additive Manufacturing process. A project was designed that requires the students to create "a hurdle robot that can jump over an obstacle". For students to achieve this task, a laboratory manual was designed to guide the students to build the robotic car using Additive Manufacturing machine and existing CAD software package. The findings show that PBL approach using AM facilities at the university assist in stimulating the imagination and innovation of the students, because the approach allows the students to use their innovative ideas and knowledge to develop a robot car design (Tang and Mo, 2015).

Furthermore, Williams and Seepersad (2012), identifies one of the key barriers to widespread of AM technologies adoption to unfamiliarity of students to AM technologies. At the University of Texas, a problem-based learning approach was introduced to a an undergraduate/postgraduate course titled "Design for Additive Manufacturing". The PBL approach to learning allows the students to gain hands-on experience with AM technologies. The students were divided into small group of (3 people) and requested to explore AM technology limitations by designing and measuring a part for benchmarking using three metrics, that is, resolution, accuracy and surface finishing. Designing of the part enables the students to observe the effects of potential sources of AM build error (for instance, layer thickness, orientation, presence of support material, etc.) on the metric chosen and students were guided by AM instructors (Williams and Seepersad, 2012). As each group submitted their part design, the design is built using a Laser Sintering machine – a Polyjet 3D printing machine, and a Fused Filament Fabrication machine (FFF). Conclusively, the students present their final design part to the class in order to educate their peers, that is, what the group learn about resolution, accuracy and surface finish. The findings from this study shows that Problem-based learning approach assist students to acquire a more complete understanding of concepts and ideas rather than receiving a traditional instruction of the part design. This approach also increases students' knowledge, skill acquisition and transfer, positive improvement in transferring knowledge across different contexts (Williams and Seepersad, 2012).

Ferchow *et al* (2018) study on 'Design for Additive Manufacturing' enables graduate students to design using AM technology through teaching (lecture) and experience transfer (Problem-based learning). A Switzerland university called "ETH Zürich" introduced a course in AM for graduate students at master's degree level in the field of Mechanical Engineering. The main aim of this course is to allow students gain hands-on experience in the possibilities and restriction of DfAM. The course is based on Experience Transfer Model (ETM) and divided into two parts: Lecture and Team project (Ferchow *et al*, 2018). The lecture part allows students to gain explicit knowledge of DfAM and the concept behind the team project part is based on Problem-Based Learning approach. During the course, the graduate students gained insights into the following topics [AM concept, design of AM prototypes, data preparation, post processing, and AM process chain concept]. A systematical approach was used for team project which gives the students the privilege to receive expert feedback and real-life experiences. The final AM parts showed that all teams were able to successfully design and manufacture AM parts. The physical outcomes of the program showed that the graduate students are able to design AM optimized parts without falling back into the traditional design patterns of conventional manufacturing processes. At the end of the lecture series, a survey was conducted and majority of feedback from the students were positive (Ferchow *et al*, 2018).

3.6 Additive Manufacturing Laboratory Concept at the Universities

Establishment of AM/3D Printing laboratories is crucial for effective AM education at the university. Globally, different universities have started establishing AM/3D printing labs within their Faculty of engineering and creating an enabling environment to empower people (students/academics/industry professionals). Such an initiative stated at Vaal University of Technology in South Africa in 2011 where an Idea 2 Product (I2P) lab was launched and currently, the I2P lab concept has been adopted and implemented in more than 25 platforms active internationally (Campbell and De Beer, 2017). Colorado State University in the United Stated Launched an I2P lab in 2013 by David Prawel which was modelled after the I2P lab founded at Vaal University of Technology. The Colardo State University I2P lab is well-equipped with RepRap 3D printers within the Department of Mechanical Engineering to assist students in gaining fundamental knowledge of 3D printing technology and hands-on experience of the technology (Wohlers and Huff, 2017).

Recently, the Department of Engineering Technology at the Miami University in Ohio launched a new AM laboratory to support design instruction and research in engineering technology. The new AM lab is partially funded from the state equipment grant which allows them to acquire 3D printers and 3D scanners for training engineering technologists using AM techniques (Bal and Abatan, 2017). Similarly, Nanyang Polytechnic in Singapore also adopted the I2P lab concept to establish their AM laboratory known as “AM Teaching Factory concept” and the laboratory is used for training students and industry professionals on relevant AM technologies that have to do with real-world or industry applications (Wong *et al.*, 2014).

Most of the AM/3D printing laboratories across different universities worldwide are modelled after the Idea 2 Product lab concept at VUT in South Africa as stated by (Wohlers and Huff, 2017); although most universities don’t name the 3D printing lab at their universities “Idea 2 Product” except Colorado State University, but some universities called their AM/3D printing laboratory names such as: Additive Manufacturing centre/lab, 3D printing library, 3D printing studio, 3D digital lab, Creative Machines lab, 3D printing lab, etc. The primary aim of AM/3D printing laboratory at the universities are designed to assist students and academics to have basic knowledge of AM and for research purposes; and more so, to gain hands-on experience while working with the demands of the fledgling AM/3D printing works coming from the industry partners (Dickens *et al.*, 2016; Lin *et al.,* 2012 and Hague *et al.*, 2016).

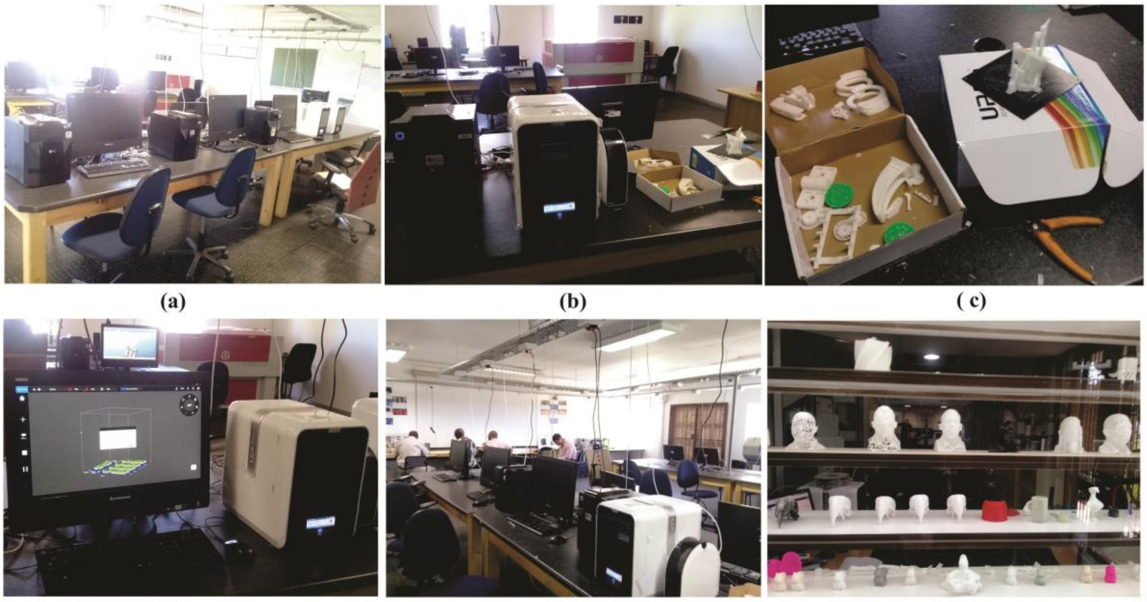
In conclusion, establishment of AM/3D printing lab at any university could serve as a platform to introduce or promote AM education at the university; and enhances diverse AM research activities. The next section of this chapter presents an overview of 'Idea 2 Product lab at the South Africa universities with more reference to Vaal University of Technology.

3.6.1 Idea 2 Product Lab Concept in South Africa

The Idea 2 Product (I2P) ® Lab concept was launched in 2011 at the Vaal University of Technology by a team of researchers. The aim of Idea 2 Product lab is to serve as platform to transfer technology and innovations; and emerging advanced manufacturing technologies (such as AM) between the academic institutions and industries. I2P lab is recognized as self-help laboratory, fitted with entry-level FDM 3D printing machines for education, creative engagement, innovation, and product development. The lab is purposefully designed to empower people and develop the community. In an ideal environment, Idea 2 Product lab enables university-industry collaboration (CSU Ventures, 2013). With the use of Idea 2 Product lab, the younger generation of entrepreneurs and students at the university have the privilege to bring their initial ideas, innovations and creativities into tangible 3D products (Havenga, 2017).

According to Du Preez *et al.* (2016) one of the very successful educational initiatives in South Africa is the establishment of "Idea to Product" lab at the VUT. An I2P lab is a strategic intervention lab (i.e. an innovation and job creation strategy driven solution lab). This lab provides individual from the Southern Gauteng region with appropriate skills development, infrastructure for entrepreneurs to develop new products that can be tested and modified in the market place based on customer needs. Figure 3.8 shows the Idea 2 Product lab at the VUT Sebokeng campus with well-equipped computers and entry-level FDM 3D printers.

Presently, the VUT's I2P lab concept gives a new home-grown 'technology transfer model' and through this medium, people are being empowered and provided with the opportunity for personal fabrication using entry-level FDM 3D printing systems. I2P lab has served as a catalyst in creating an innovation culture within the host university and amongst innovators in the neighbouring communities or regions (Campbell and De Beer, 2017). Another primary aim of I2P lab is to provide necessary infrastructure to produce small batches of niche products and it is expected to make significant contribution towards jobs creation and to help poor community's regions in boosting their economic level (Campbell and De Beer, 2017).



(a) (b) (c)

(d) (e) (f)

Figure 3 8: The Idea 2 Product lab at the VUT Sebokeng campus.

(a, b, d, e) Show the arrangement of the computer systems and entry-level 3D printers; while (c, f) shows samples of the 3D printed parts

3.6.2 Entry-Level FDM 3D Printers as a Tool for Additive Manufacturing education

Entry-level FDM 3D printing machines can serve as a tool for AM education at any educational level, because it is very affordable when compared to the high-end industrial additive manufacturing machines which are very expensive. The cost of entry-level FDM 3D printer has reduced drastically in last few years and this is an indication that more people will have access to affordable desktop 3D printers in the coming years.

- **Entry-Level FDM 3D Printers as a tool to Train People using Idea 2 Product ® Lab Concept**

Different studies have shown that entry-level FDM 3D printers can be used to train people such as (university students, high school leaners, entrepreneurs, professionals, and community members) and providing them with fundamental knowledge and hands-on-experience of AM technology. Evidence from I2P lab at VUT campuses has supported this fact. According to Campbell and De Beer (2017) since the inception of the Idea 2 Product lab, between 2011 and 2016, approximately 7500 students have been trained with entry-level FDM 3D printers and over 20,000 parts have been designed and printed out or manufactured. In addition, between July 2016 and July 2017, 200 people were trained using the same I2P lab facilities at the VUT, which consist of 90 males (45%) and 110 females (55%); and the nationality of people trained were 190 South African citizen (95%) and 10 foreign nationals (5%) as shown in the full paper in appendix G. The I2P lab is well-equipped with computers directly connected with approximately 20 entry-level FDM 3D printers with internet facilities.

This is an indication that South African government (Department of Science and Technology) is gradually achieving one of the primary aims for developing South Africa Additive Manufacturing strategy (Du Preez *et al.* 2017). Entry-level FDM 3D printing facilities can serve as a stimulated manufacturing environment for students within the university and communitive to become more creative, innovative and design faster (Makerstation, 2017). In conclusion, an entry-level FDM 3D printer is considered suitable for AM education at all educational level because of its capability to train and equip people with fundamental AM skills.

- **Entry-Level FDM 3D Printers as a Platform for Technology Transfer using the Idea 2 Product ® LAB concept**

Schelly *et al.* (2015) study explain that "a democratized use of entry-level AM machines imposes the need for educating people to advanced 3D modelling by using professional CAD software packages or even open freeware packages with enhanced modelling function". Entry-level FDM 3D printing machines can be a successful tool in the formation of engineers both in the industry and colleges/universities, this allows them to benefit or gain hands-on experience and thereby acquire capabilities from both engineering design skills and new advanced manufacturing technologies currently referred to as "Industry 4.0" (Schelly *et al.*, 2015).

In addition, Schelly *et al.* (2015) study as relating technology transfer and the involvement of people (students/interns/academics/professionals/community members) using entry-level FDM 3D printers could enhance people's interest to advance to high-end additive manufacturing machines, for example, people can start with entry-level 3D printers and develop interest in the AM technology, and later advanced to operate high-end industrial AM machines.

3.7. The SWOT analysis to evaluate the present and future prospects of AM education

A SWOT analysis is a tool used to analyse the strengths, weaknesses, opportunity and threats in businesses, organization and research. SWOT analysis can be referred as a framework to assist the researchers to identify and prioritize research goals and can be used to further pinpoint the strategies of achieving the set goals (Ommani, 2011). The strengths and weaknesses are referred to as internal factors while the opportunities and threats as the external factors.

Therefore, in this section, SWOT analysis is used to evaluate the present and future prospects of AM education and research at South African universities.

Table 3 1: The SWOT analysis to evaluate the present and future prospects of AM education and research.

Strengths (S)	**Weakness (W)**
The availability of high-end AM machines at selected SA universities is a major advantage in promoting AM education and research in area such as aerospace, medical, automobile and industrial designs. Establishment of more 12P lab at SA high schools, colleges and universities will enhance innovative and creative thinking among students and develop interest in STEM education. In the coming years, RAPDASA will serve as the right vehicles to promote AM activities in SA through the annual international conference and to create global awareness. Over the years, Technology Transfer has played a major role in advancing AM technology at SA universities and will continue to play an important role by providing both theoretical and practical knowledge to students, academia, entrepreneurs and professionals in SA.	To effectively promote AM education, there is a need for SA government through DST to create more centre of excellent in of AM and Research Chair in AM at selected universities. SA AM strategy aimed to create an enabling capability development environment for AM technology and promote AM education at all levels, e.g. colleges and universities. To achieve this aim, more AM in-house facilities needed at SA's universities. To encourage more postgraduate students and young researchers to attend annual RAPDASA conference and to get expose to AM technology and research. RAPDASA conference committee should increase their scholarship to allow more people to attend. More AM technology awareness need to be done at SA Higher Education Institutions (HEIs) in order to increase AM professionals/experts because insufficient AM personnel/educator is one of the factors identified limiting the advancement of the technology in SA.
Opportunities	**Threats**
An introduction of a postgraduate degree, for example "MSc or MEng" program in AM at major SA universities. This will serve as opportunities to increase the number of professionals and expertise in the field of AM in SA. Availability of large amount of Titanium in SA creates a great opportunity for production of medical implant and titanium prosthetic. Likewise, SA platinum powder will enhance the jewellery industry in SA using AM technology. Efficient University-Industry collaboration would enhance AM research activities at the university and expose students and academic to AM education. Such collaboration can attract more internship for students, and funding for the universities to conduct research in emerging areas of AM technology. CUT indicated that a course in mechanical engineering was introduced to suit AM technology within the SA context. To enhance AM technology growth among students at SA universities; an inclusion of a course or some topics in manufacturing courses related to AM in the undergraduate curriculum at the universities will serve a good platform to educate people about AM technology and promote a career path in AM field.	High cost of AM system and the materials, most especially the high-end industrial AM machines is a threat to many HEIs and industries and it is delaying the adoption of AM technology. Lack of effective framework for AM education for SA universities is another threat that need to be addressed in the future. For more quality and advanced research in AM, consistent funding from NRF/DST and other funding bodies is needed, for SA AM research to compete globally in cutting edge research.

3.8 Chapter summary

This chapter has presented the importance of AM/3D printing in the education sector and reviewed recent studies on AM education from various scientific open journals/publications, master dissertations and doctoral theses. This chapter shows recent involvement of some universities in AM education worldwide and describes the establishment of AM/3D printing lab in various universities globally, for instance, in South Africa, there is ‘Idea 2 Product lab’ at Vaal University of Technology/Stellenbosch University/North-West University; and these are good platforms to introduce and promote AM education at the university. Lastly, This chapter also presented a SWOT analysis that evaluates both the present and future prospects of AM education and research at South African universities

The next chapter is the continuation of ‘literature review’ chapters. The chapter explores the various applications of AM across different sectors such as (medical and dental, aerospace and defence, automotive, electronics, tooling and moulding, building and construction, biomedical, education). The next chapter also look at the various contributions and technological advances from the universities, manufacturing industries, and 3D printing bureau services or companies. and how these contributions have enhanced the growth and development of AM technologies globally.

Chapter 4

4. Applications of Additive Manufacturing across Different Sectors

This chapter explores various industrial applications of additive manufacturing from a wider perspective as applies to South Africa and the world at large. Different literature from different articles, journals, publications and open scientific repository were consulted. This chapter also looks at the various contributions and technological advances that the universities, manufacturing industries, 3D printing companies and research institutes/councils have contributed to enhance additive manufacturing growth and development over the years.

4.1 Global Perspective of Additive Manufacturing Applications

From a global perspective, advances in AM technology has brought about different application areas of AM across various sectors. All over the world, many companies have greatly involved in the production of more 3D printers and thereby, making AM system accessible to everyone. Various studies have shown a tremendous growth in 3D printing market in the past three or four years which implies that several opportunities await AM technology in the nearest future (Wohlers, 2014).

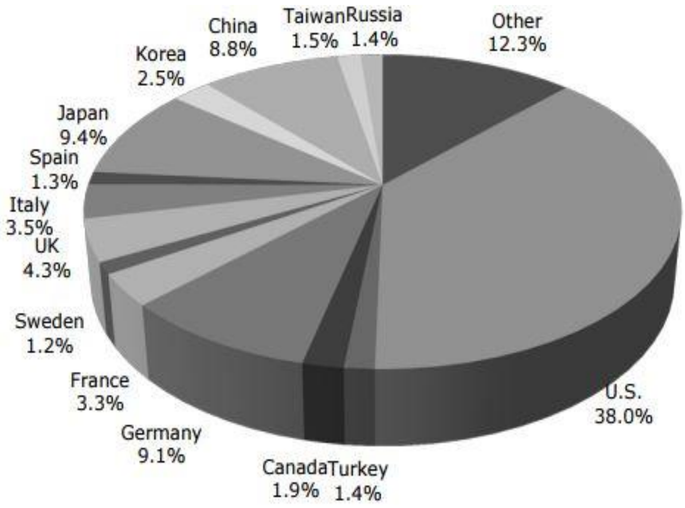


Figure 4. 1: Regional distribution of producers of AM and 3D printers

Source: Wohlers (2014: p18).

Majority of the manufacturers of AM machines are based in United States (i.e. 38%) as shown in Figure 4.1, while Germany, Japan, China takes approximately 9% of the AM market share each (Van der Zee *et al*, 2015). From a regional perspective, countries like Canada with 1.9%, Turkey, Sweden, Spain, Russia, and Taiwan are still lagging behind in the production of AM/3D printers with 1.4%, 1.2%, 1.3%, 1.4% and 1.5% respectively. The United Kingdom, Italy and France takes 4.3%, 3.5% and 3.3% respectively in the production 3D printers. Meanwhile 12.3% takes “others” and this implies that the position of South Africa is among the ‘others’ as shown in Figure 4.1 (Wohlers, 2014).

Globally, as AM technology is rapidly growing and expanding capabilities across different sectors. There is a need for statistical analysis of determine the number of AM users and to identify the active sectors of this technology. Wohlers Associates Inc in 2014. conducted a survey among 29 manufacturers of professional-grade industrial AM systems (i.e. those that sell for $5,000 or more) and 82 service providers worldwide. During the survey, each company was asked to indicate which industries they serve and the approximate revenues (as a percentage) that they receive from (QTR, 2015; Wohlers, 2014). The survey shows that some sectors are lead users of AM technology worldwide and such sectors are aerospace, automotive and electronics.

The medical sector is also exploring and embracing this technology, most especially in the dental field as the use of 3D printed part is fast growing in this area (Van der Zee *et al.* 2015). Wohlers report in 2014, shows the users of AM by sectors. The academic institution takes 8.2% which implies that many universities all over the world are yet to be involved in AM research as shown in Figure 4.2. Nevertheless, there is a tremendous growth in academic research within the AM from different universities and this has led to various ongoing research project from different research groups in the area of - rapid product development, metal casting, high performance tooling, medical modelling, tissue engineering, architectural modelling and reverse engineering (Wohlers 2014: 214; Van der Zee *et al.*, 2015).

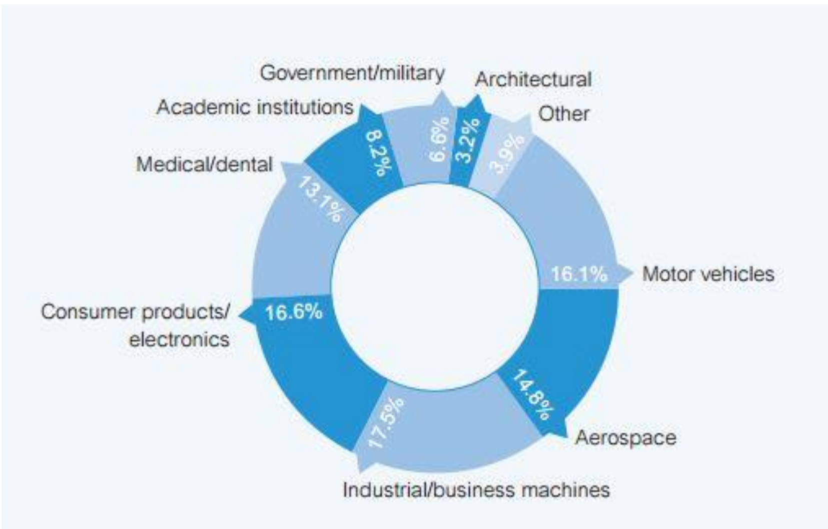


Figure 4. 2: Additive manufacturing/3D printing users by sectors

Source: Wohlers (2015).

The consumer products and electronics take 16.6%, industrial and business machines users have higher percentage of 17.5%. The architectural and government/military users take 3.9% and 6.6% respectively, which mean there is need for more awareness and investment in AM in this sectors and "other" category in the survey analysis includes a wide range of industries like oil and gas, sporting goods, commercial marine products, etc. (QTR, 2015) as shown in Figure 4.2.

Figure 4.3 describes how different organisations and companies across the globe are currently using industrial AM systems for numerous applications. The survey results indicate that 29% of the companies are using AM technology to produce "functional part" i.e. short run, series production and prototyping. The results also show that 19% of the companies are using AM technology or parts for "fit and assembly prototypes" (Van der Zee *et al.*, 2015; Wohlers, 2014). The survey results further indicate that "patterns for metal casting" and "patterns for prototype tooling" takes approximately 10% each while the education, visual aids and presentation models altogether took approximately one fifth of the survey results. According to Van der Zee *et al.* (2015) despite rapid growth within the AM technology, the use of AM in industry is still marginal thus far, if it is measured by the share of total production values. However, the current applications as shown in the results of the survey gives a hint where AM could play a significant role in the future if more investments can be committed by private organizations, research institutes and academic institutions across the world.

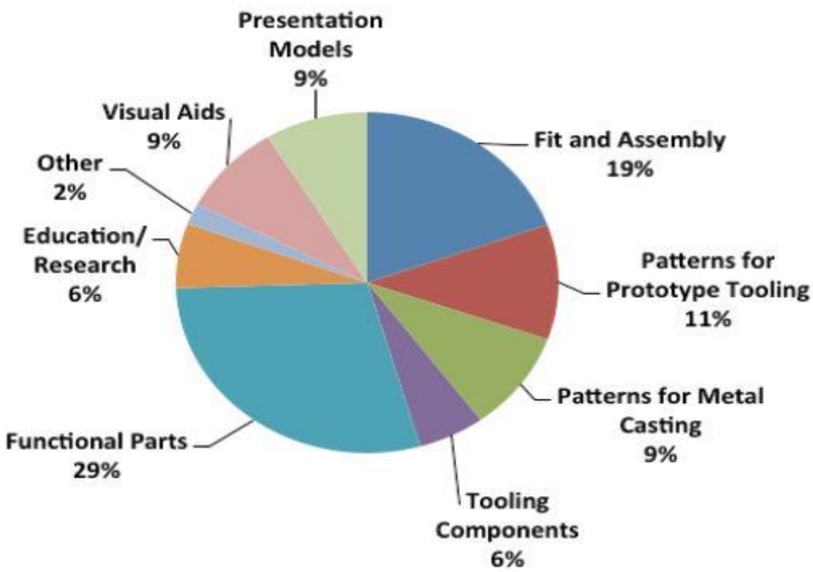


Figure 4. 3: Current application areas/fields in additive manufacturing

Source: Wohlers (2014: p20).

Wohlers (2016) report provides a comprehensive explanation on the state of the global AM industry today and the report was based on a survey conducted among 51 industrial system manufacturers, 98 service providers, 15 third-party material producers, various desktop 3D printer manufacturers and 80 3D printing experts from 33 countries across the globe. The 2016 results show that the AM/3D printing sector has grown rapidly by 1 billion US dollars to a total of 5,165 billion US dollars as presented in Figure 4.4. Wohlers Associates report estimates that more than 278,000 desktop 3D printers (with priced under $5,000) were sold worldwide in 2015 alone. Wohlers (2016) explains that "despite some challenges within the 3D printing industry, growth was particularly apparent in two distinct and seemingly opposite sectors - industrial metal additive manufacturing and desktop 3D printers" (Kira, 2016).

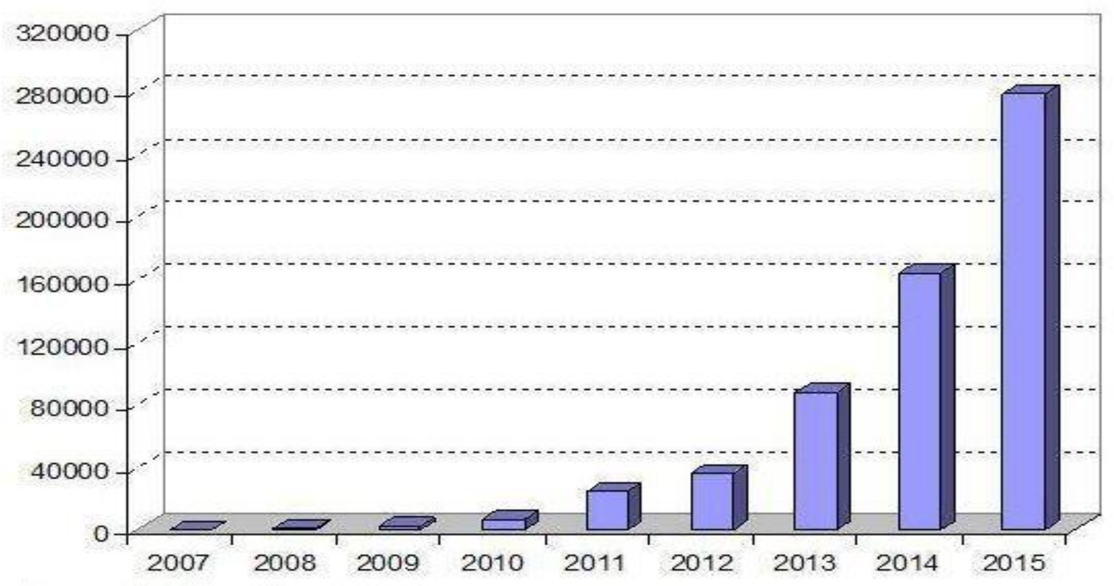


Figure 4. 4: Global Market Growth of 3D Printing Industry (2007-2015).

Source: Wohlers Report 2016.

South Africa is not left out in the global revolution of AM technology and it has a very good position within the African continent. According to Du Preez, *et al.* (2016) a number of promising market applications have been identified for AM in South Africa. South Africa has abundant mineral reserves and is the world's second largest producer of IImenite and Rutile, from which Titanium (Ti) pigment is extracted. More so, South Africa is the second largest mining producer of Vanadium and Aluminium. Vanadium are key to titanium alloy which is use for medical and dental implants, and aerospace manufacturing industries (Du Preez *et al.* 2016). Du Preez *et al.* (2016) stresses that AM technology is used for prototyping and tool production in different application areas among South African industry which has contributed positively to South African Gross Domestic product (GDP).

Therefore, AM has a very great potential to revitalize South Africa's tooling and foundry industries through the introduction of innovative technologies that will improve the tool performance and shorten the production and delivery time (Du Preez *et al.* 2016). Additive manufacturing applications have the capacity to impact the South African small, medium and micro enterprises (SMME). In 2016, South African AM experts launched the "South African Additive Manufacturing Strategy" with the aim to ensure AM competitiveness on a global market place (Du Preez *et al.* 2016). Therefore, AM in South Africa has a great prospect to revolutionize the economy of the country and other numerous industries.

4.2 Industry applications of additive manufacturing technology

This section of the chapter explores different key industry application areas of AM/3D printing technology in today market and shows the numerous impacts of AM applications.

4.2.1 Aerospace and Defence (A&D) industry

According to Guo and Leu (2013) aerospace components often have complex geometries and are manufactured using advanced materials, such as titanium alloys, nickel super alloys, special steels or ultrahigh-temperature ceramics since most aerospace components are very complex, costly and time-consuming to manufacture. Aerospace functional parts with complex geometries can be manufactured faster at a moderate cost using AM technology. Some of the great benefits of AM to aerospace industry are reduction in raw materials used, weight savings, lower fuel consumption and reduction of CO_2 emissions. This makes AM technology mostly suitable for the aerospace and defence industries. Figure 4.5 shows some samples of aerospace parts manufactured using AM technology; (a) is the nickel alloy jet engine combustor produced by DMLS technology, (b) an air ducts parts (c) cobalt chrome aerospace gas turbine swirler manufactured through the direct metal laser sintering technology.

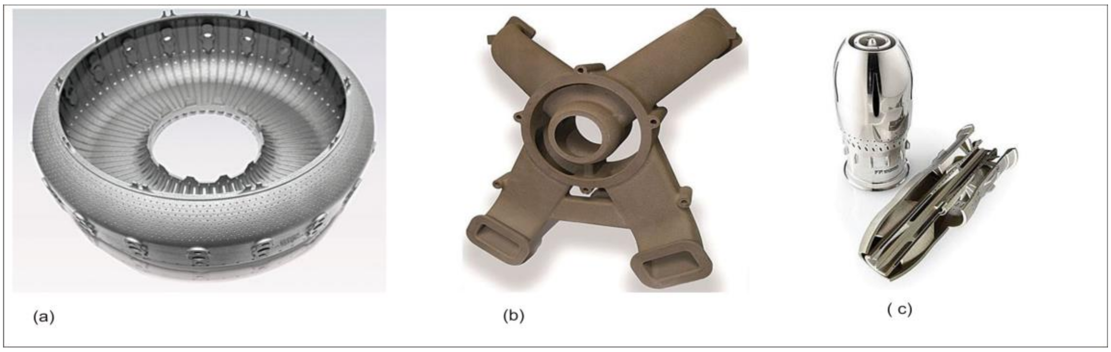


Figure 4. 5: Samples of 3D printing parts for the aerospace and defence industry

Source: EOS of North America Inc.

In 2015, Stratasys and Airbus announced that the new A350 XWB aircraft contained over 1000 flight parts made by 3D printing technology. FDM technology were used to manufacture the flight part and the aircraft was in December 2014 (Stratasys, 2015). The 3D printed parts were designed, manufactured and fixed to the aircraft in order to replace the traditionally manufactured aircraft parts. The 3D printed parts were introduced so as to increase supply chain flexibility and to allow Airbus to meet its delivery commitments on time. Using 3D printing technology for A350 XWB aircraft has helped Airbus to save manufacturing costs, reduce manufacturing/production time, reduction of CO_2 emission and meeting appropriate market deadlines (Stratasys, 2015). Boeing – a commercial airplanes company also utilizing the AM technology to printing airplanes parts. Table 4.1 shows the current and future applications of AM/3D printing technology within the aerospace and defence (A&D) industry.

Table 4. 1: Current and future application of AM within the A&D industry. (**Source**: QTR, 2015; 3DPR, 2014)

Industry	Current Applications	Future or Potential Applications
Commercial Aerospace & Defence	• Concepts modelling and prototyping • Printing low-volume complex aerospace parts • Printing replacement parts • Structural and non-structural production parts • Low-volume replacement parts	• Embedding additive manufacturing electronics directly on parts • Printing aircraft wings component • Printing complex engine parts • Printing repair parts on the battlefield • Other structural aircraft components

In the same vein, the South African aerospace industry and companies (Aerosud, Adept Airmotive, Denel Aviation and Dynamics, and Airbus DS Optronics) have adopted AM technology for final parts production. The companies have used AM technology for prototype development, and this has assisted the A&D industry to speed up their product development cycle (De Beer *et al.* 2016).

4.2.2 Automotive industry

Currently, AM technologies are used extensively within the automotive industry. AM is used at different levels of automobile production such as, concept modelling, functional testing, rapid manufacturing, and production planning (Frost & Sullivan, 2007). AM is use for prototyping and direct manufacturing of small, complex, and non-safety-relevant parts within small series production (Bourell *et al.* 2009). Figure 4.6 shows some samples of automotive parts manufactured using AM technology (a) A pump housing for the automotive sector (b) A water pump wheel for the motor-sports industry manufactured using new alloy and metal laser melting (c) A car lighting parts manufactured using SLA technology.

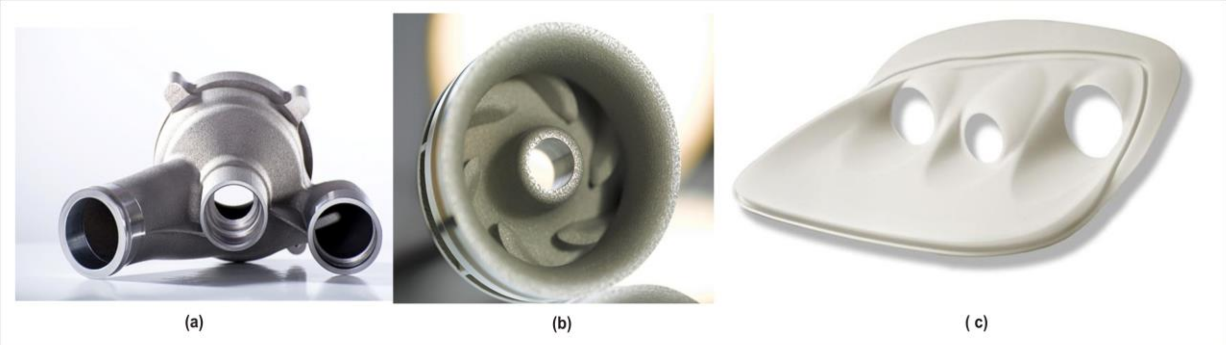


Figure 4. 6: Samples of 3D printing parts manufactured for the automotive industry

Source: SAE 2015; AxisProtypes 2015.

Application of AM technologies has been propagated continuously within the automotive industry since 2000 (Gausemeier, 2011). Many automotive industries such as (BMW, Ford, Honda and General motors) are currently using AM technology as an important tool for designing and development of automotive components because the technology helps to shorten the development cycle and reduce manufacturing and production cost (Guo and Leu, 2013). The automotive industry is a major users of AM technology as indicated in Wohlers report in 2015, as automotive industry takes 16.1%. The motor sports sector constitutes an important area where AM technology is being used mostly because this sector requires a high performance and low weight motor sport cars and also, motor sports sector have highly complex structures and low production volumes and this makes AM suitable for this sector (Gausemeier, 2011; Guo and Leu, 2013).

Due to daily increasing competition within the automotive industry, the industry is looking for a way to reduce the time to market and to expand the market share of advanced manufacturing technologies such as AM technologies (QTR, 2015). According to Guo and Leu (2013) AM processes have been used to make small quantities of structural and functional parts, such as engine exhausts, drive shafts, gear box components and breaking systems for luxury, low-volume vehicles. Most South African automotive industries are not using AM technology to its full potential but several large international car manufacturers in the country have their own AM machines for prototyping, testing and optimization. The use of AM technology locally can improve the efficiency and create competitive advantage for South African automotive industry (Du Preez *et al.* 2016). Figure 4.7 shows the present and future AM applications in the automotive industry.

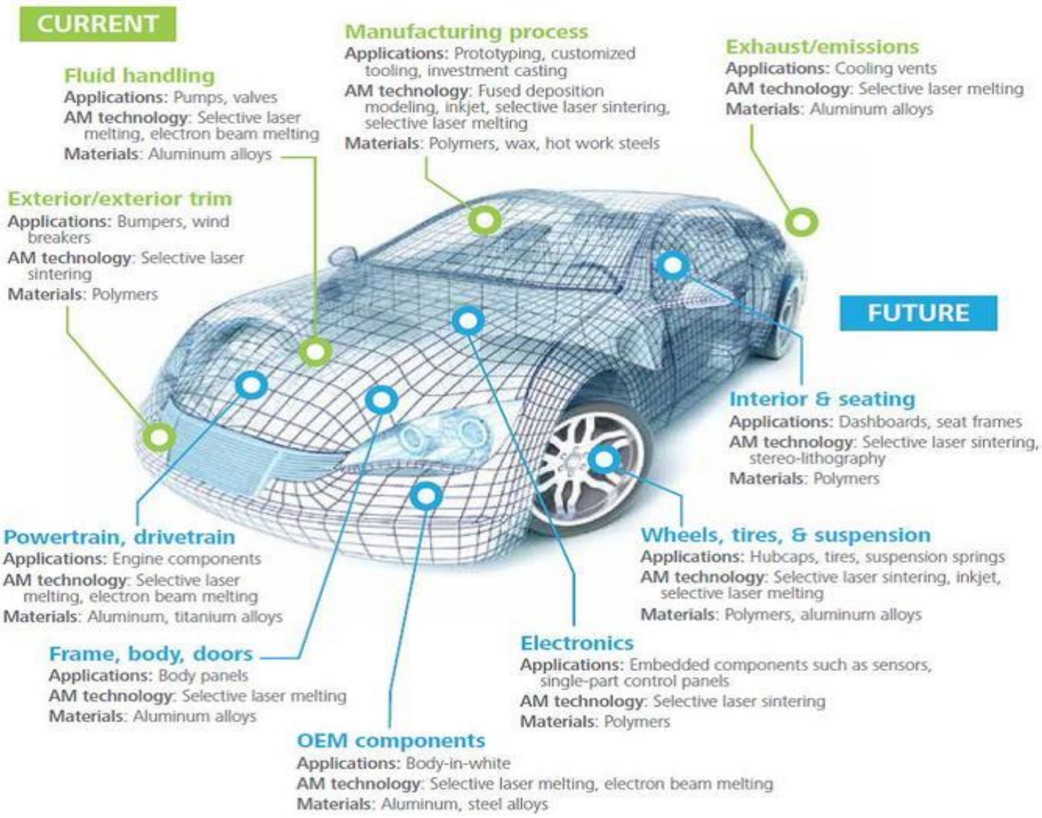


Figure 4. 7: Current and future applications of additive manufacturing within the automotive industry
Source: Deloitte University Press 2014

4.2.3 Electronics Industry

In recent years, the electronics industry has been characterized by a rapid technological development and continuously shortening product life cycle (Gausemeier *et al.* 2013:28). In many electronic industries, AM technology has been introduced to accelerate development and manufacturing processes. AM enables functional integration and embedding electronics into all kind of geometries, for instance the technology is capable of responding to the major trends of electronics industry, such as miniaturization, functionally integrated (micro) systems, high performance, optoelectronics, embedded technology, energy-saving electronics, Halogen free, flexible circuits, printed electronics, etc. (Gausemeier *et al.* 2013:28; Starr, 2011).

Electronic industries have a wide range of applications and it ranges from computers and mobile phones to cars (Gausemeier *et al.*, 2011). Technological advances are rapid which shorten the lifetimes of electronics. Electronics products are often small and require high-precision tools for the manufacturing processes, and new manufacturing equipment are needed frequently (QTR, 2015). AM technology can enable manufacturing equipment to meet the challenge of the rapid technological advancements required for new products in the electronics industry (Frost & Sullivan, 2007). Gausemeier *et al.* (2013) stress that combining AM technology and printed electronics circuitry has great potential to completely make the electronics industry production processes or cycle to be more efficient with quality products and at the same time using less material and less production cycle.

According to Gausemeier *et al.* (2011:23) AM technology is already widely spread within the electronics industry; especially, in the production of manufacturing and tools equipment and the production of embedded electronics using AM technology. Gausemeier *et al.* (2011) maintain that as AM applications are significantly increasing its potential because of the emerging new materials (such as polymers, metal-based materials and inks), inkjet printing methods will be at the forerunners of AM technology considered suitable for the electronics industry (Gausemeier *et al.*, 2011).

Figure 4.8 below shows samples of electronics components printed using AM technique. (a) The internal electronics, battery and 3D printed shell with motion tracking points on the cap, the case was 3D printed (b) The circuit board produced from CAD data for specific geometries and shapes and the design processes was more faster (c) the first headphones with mass-produced 3D printed parts, all the parts were printed with variant of nylon which starts as powder and later melted in a series of layers to produce the final product using Selective Laser Sintering technology.

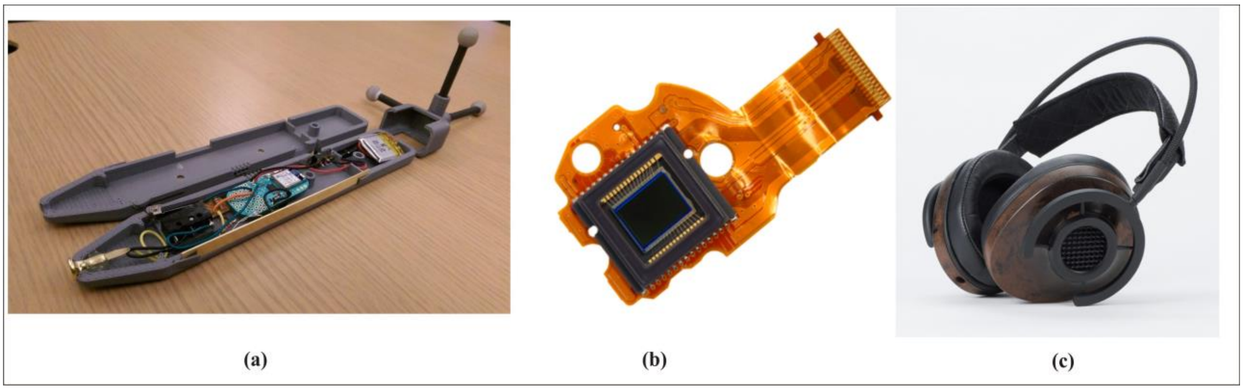


Figure 4. 8: Samples of electronics components printed using 3D printing industry

Source: (a) DIY3DPrinting 2016 (b) Agent3D 2016 (c) Sculpteo 2014.

4.2.4 Medical and Dental industry

The medical industry is another major user of AM technology in the world. The technology is used to create customized medical devices that are closely replicate the human form (Ford, 2014). Application of AM technology is rapidly expanding the medical and dental industry and the technology is expected to revolutionize the healthcare sector in the future (Ventola, 2014). According to Klein *et al.* (2013) as cited by Ventola (2014) the medical industry uses AM/3D printing across a wide range of applications such as (tissue engineering for transportation i.e. tissue and organ fabrication; creation of customized prosthetics; implants and anatomical models; and also, in the pharmaceutical research for drug dosage formulation, delivery and discovery).

Furthermore, Klein *et al.* (2013) stated that "one of the most evident uses of AM/3D printing technology in medicine, is the use of high-definition computed tomography scans to produce customized bone prosthetics. The use of custom-made porous titanium or ceramic prosthetics may be particularly interesting to spine surgeon because of its capacity to serve as a scaffold for bone in growth. However, spine surgery is at the forefront of AM field in medicine because 3D bio-printing has been used experimentally to create intervertebral disks for possible disk replacement (Klein *et al.* 2013). Therefore, application of AM technology in medicine and surgery has greater advantages to the medical sector such as - cost-effectiveness, enhanced collaboration among medical experts, increase in productivity and easy customization and personalization of medical products, drugs and equipment (Ventola, 2014; Schubert, 2014; Banks, 2013).

Presently, the models created using 3D printing have not yet been used in planning brain surgery and however, the models have been used to plan liver transplantations by pioneering Japanese surgeons. Maki Sugimoto, a surgeon at Japan's Kobe University Hospital, has been using replicas of patients' organs for surgical planning purposes, that is, to understand how to carve a donor's liver to fit into the recipient's abdominal cavity with minimal tissue loss as shown in Figure 4.9. Figure 4.9 shows samples of customised 3D printed components for the medical and dental industry; and basically, these customized 3D printing models are used for surgical planning, teaching and practicing. (a) 3D printing replica of liver for surgical planning purposes (b) Skull prosthetic created using 3D printing technology for skull implantation (c) from left to right - complete jaw model in form of a solid piece to check for occlusions, saw-cut model with pinholes, model with removable stumps for dental application.

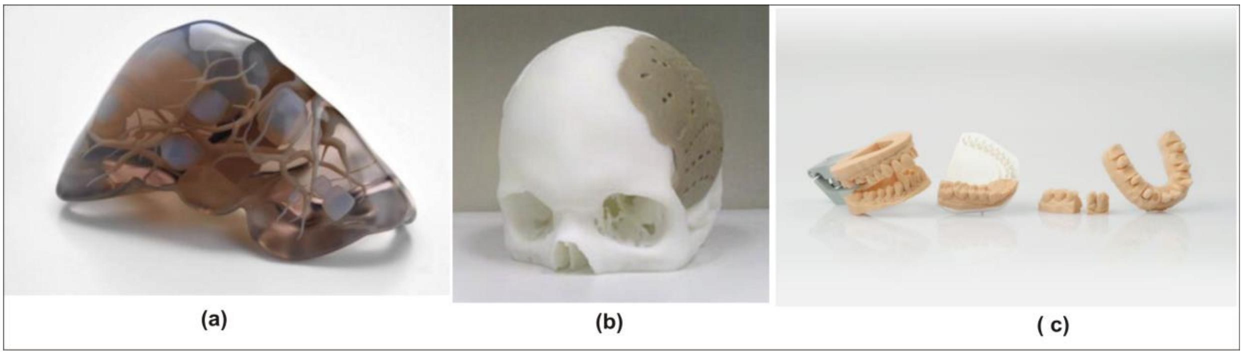


Figure 4. 9: Samples of 3D printed components for the medical and dental industry

Source: (a) and (b) Klein *et al.* 2013; (c) EOS 2013.

According to Ventola (2014) application of 3D printing technology in the medical and dental industry allows nearly any imaginable geometry to be produced both for implants and prostheses purposes through the translation of X-ray, Magnetic Resonance Imaging (MRI), or Computerized Tomography (CT) scans into digital. stl 3D print files. As a result of this, additive manufacturing technology has been successfully used in the healthcare sector to make both standard and complex customized prosthetic limbs and surgical implants, sometimes within 24 hours (Ventola, 2014). In the past, before implant can take place clinically, the surgeon had to validate it and which is time consuming-process, but the use of AM/3D printing technology has made life easy for the surgeon as dental, spinal, and hip implants are been fabricated (Banks, 2013; Ventola (2014).

In several field of dentistry, AM has become established for laser sintered dental prostheses and this has almost completely replaced precision casting in some countries (EOS, 2013). Von See and Meindorfer (2016) explains that various AM processes are used to manufacture technical dental restorations, and this is generally involving the manufacture of semi-finished or finished parts. The process involves the joining, bonding, sintering or polymerising together small volume elements (Von See and Meindorfer, 2016). At the Centre for Rapid Prototyping and Manufacturing, a number of facial implants have already been developed, manufactured and implanted in South Africa using AM technology (Du Preez *et al.*, 2016)

4.2.5 Tooling and Moulding Industry

Development and manufacturing of tooling are one of the most expensive and time-consuming processes within various manufacturing industries, because tool production of tools contains complex geometrics and requires very high accuracy and reliability, low surface roughness, and strong mechanical properties (Frost & Sullivan, 2007; CustomPartnet. 2009). AM techniques in tooling and moulding industry is also known as rapid tooling. Rapid tooling is the rapid production of parts/components that functions as a tool, primarily mould tools such as mould inserts, as opposed to be a prototype or functional parts (Chua *et al.* 2014).

According to Cotteleer *et al.* (2014) use of AM technology in the tooling industry for fabrication of tools have reduced lead times, costs, enhanced the ability to customize and improve functionality. Tooling and moulding industry are capital and knowledge intensive industries, and many industries have adopted AM technology for tooling and moulding, and as essential part of their designs and manufacturing processes, such industries include - aeronautics, automotive vehicles, electronics, industrial products and consumer products (Wohlers, 2010).

Tooling and moulding industry spans from early stage prototypes to full scale productions and this industry is crucial for the competitiveness, efficiency, and robustness of a production system because tools are used to link final parts (products and components) and production equipment together, for instance, machine tools (Wohlers, 2010). The use of AM technology in the tooling industry covers a wide range of application areas such as casting and machining processes, and assembly jigs and fixtures (Cotteleer *et al.* 2014). The most commonly used AM materials for fabrication of tools are - plastics, rubber, composites, metals, sand and wax (Cotteleer *et al.* 2014).

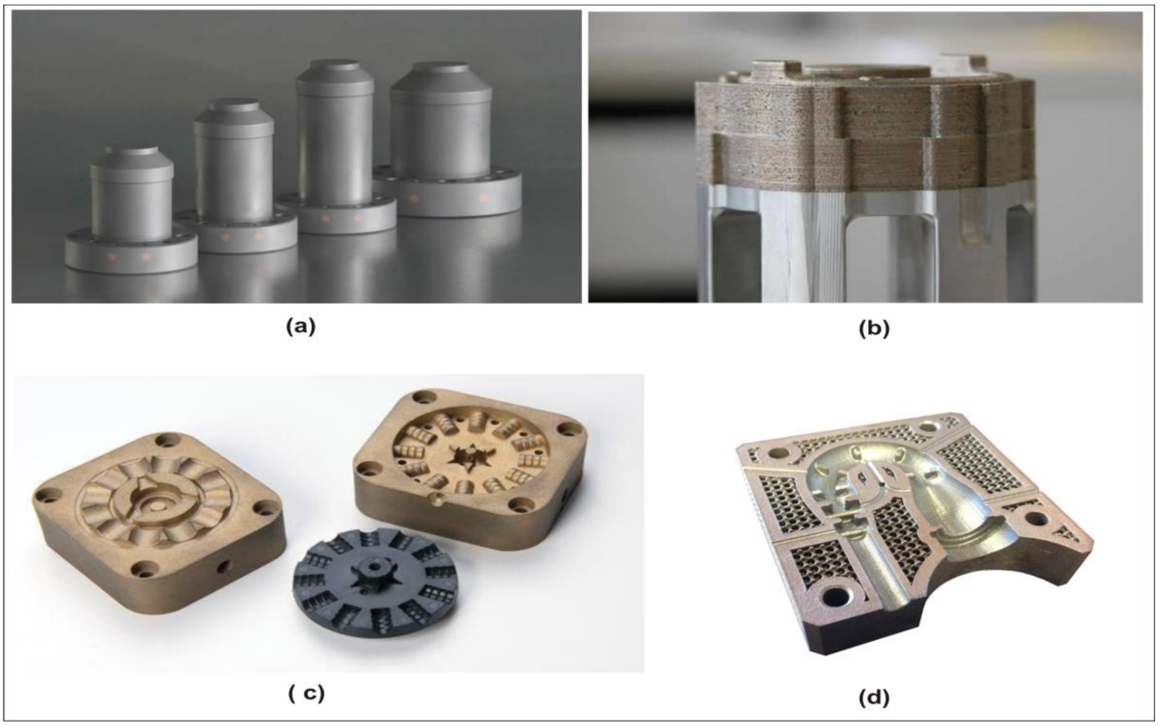


Figure 4. 10: Samples of 3D printed components in tooling and m oulding industry

Source: (a) and (b) Metal AM, 2015; (c) AM Magazine, 2014 (d) Dvorak, 2014

Figure 4.10 shows some 3D printed components for the tooling and moulding industry, (a) Sprue brushes manufactured for hot runner systems using a hybrid technique (b) Mould insert for an injection moulding tool, which has been built on an existing mould section. (c) A mould core and cavity with conformal cooling for an interactive model toy was produced using Nickel bronze material (d) A mould built with DMLS machine which makes the complexities of the design possible.

4.2.6 Biomedical industry

Additive manufacturing/3D printing technology continues to innovate and revolutionize the biomedical industry from dental products to prosthetics and tissue engineering. AM application is helping to address some challenges in the biomedical industry today (Sethi, 2015). An associate professor of mechanical and aerospace engineering and computing and information science at Cornell University which is also a co-author of a book entitled: *Fabricated: The New World of 3D printing*, Hod Lipson, says “Biomedical applications are ideally suited for 3D printing technology because they are built on this uniqueness of AM, which is the ability to make optimized and customized parts that are very complex” (Sethi, 2015).

Bioprinting is another biomedical application of AM technology (Perkel, 2015). Bioprinting is an emerging technology for fabricating artificial tissue and organ constructs. Large scale research has been conducted on bioprinting and it shows potential benefits as a future means for organ transplants (Sethi, 2015). 3D bioprinting provides additional significant advantages beyond the conventional regenerative method (which is essentially provides scaffold support alone) such as highly precise cell placement and high digital control of speed, resolution, cell concentration, drop volume, and diameter of printed cells (Cui *et al.*, 2012; Ozbolat and Yu, 2013; Ventola, 2014).

In the biomedical industry, tissue and organ bioprinting is still at an infant stage and currently, many researchers have used 3D printing technology to create a knee meniscus, heart valve, spinal disk, other types of cartilage and bone, and also for artificial ear (Mertz, 2013; Bartlett, 2013; Gross *et al.* 2014). According to Ventola (2014) proof-of-concept studies as relating to bioprinting have been carried out successfully by researchers, but so far, the organs that have been produced are miniature and relatively simple. 3D bioprinting system comes in different types, and it could be laser-based, inkjet-based and extrusion-based, while inkjet based is the most common types of 3D bioprinters (Ozbolat and Yu, 2013). According to Ozbolat and Yu (2013) 3D bioprinting deposits ‘bioink’ droplets of living cells or biomaterials onto a substrate in-line with a digital instruction to produce human tissues or organs. Recently, Cui *et al.* (2012) apply inkjet 3D printing technology to repair human articular cartilage. However, quite a number of biotechnology companies are creating tissues and organs for medical research and development purposes (Bartlett, 2013).

Figure 4.11 shows some applications of AM/3D printing technology in the biomedical industry. (a) 3D printing technology used to create a 'bionic ear' which was completed with a coiled antenna to receive sound by a researcher at Princeton University (b) 3D printed foot prosthetics using a heat cured high consistency biomedical grade silicone rubbers (c) A 3D printed of organs and tissues for medical research purposes

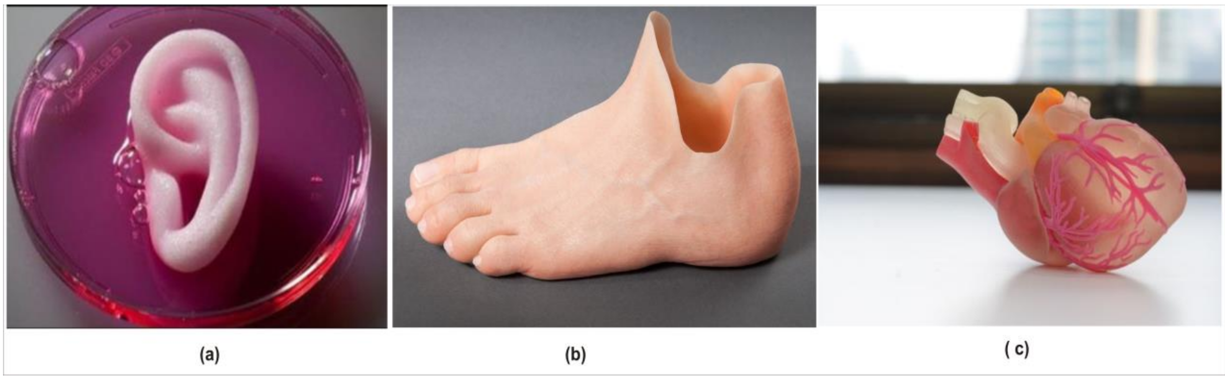


Figure 4. 11: Some applications of 3D printing in the biomedical industry

Source: (a) MRP, 2014 (b) MPN, 2015; (c) 3Printr.com 2015

4.2.7 Construction and building industry

According to Lim *et al.* (2012) the use of AM technology in the construction and building industry is beginning to move from an architect's modelling tool to delivering full-scale architectural components and elements of building, such as walls and facades. Recently, AM has been introduced into the construction industry to print houses and villas using an automated extrusion-based technology (Wu *et al.* 2016; Lim *et al.* 2012). Application of this technology in the construction and building industry could bring significant benefits to the industry, for instance, increased customization, reducing construction time, reduction of manpower and cost of construction (Wu *et al.* 2016).

Wu *et al.* (2016) conducted a critical review on the use of AM/3D printing technology in the construction industry and their systematic review shows that AM technology can be used to print large-scale architectural models and buildings. Wu *et al.* (2016) conclude that the potential of AM technology in the construction industry is limited by lack of large-scale implementation, the development of building information modelling, the requirements of mass customization, and life cycle of the printed projects.

Globally, different researchers are experimenting using different kinds of AM systems/3D printers and a wide range of raw materials and fabrication methods to advance AM technology in the construction industry and to expand the scope of potential applications of AM to print structural building components; and as well as entire building construction (Housing-Observer, 2015). The current research experimentation within the construction industry using AM systems (Housing-Observer, 2015) includes:

- Experimental research on a variety of raw materials which includes recycled plastics, bioplastics, concrete and a synthetic ‘stone-like’ material created from a combination of sand and chemicals.
- An advanced 3D printer capable of extruding multiple materials (Architect, 2015).
- To carry out a direct printing either on-site or in-factories.
- Fabrication of reinforced concrete beams (Molitch-Hou, 2015).
- Research on a variety of fabrication methods such as printing wall components in sections which can be snapped together on site; printing structural scaffolding which can be filled in with construction materials on site to create full-sized walls (Gizmodo, 2015).

Figure 4.12 shows the application of AM in the construction and building industry. (a) A one-tonne reinforced concrete bench was 3D printed in 2010 (b) a 3D printed miniature architectural models (c) a Chinese company firm 3D printed a building in a day using custom-built machine that outputs layers of construction waste mixed with cement.

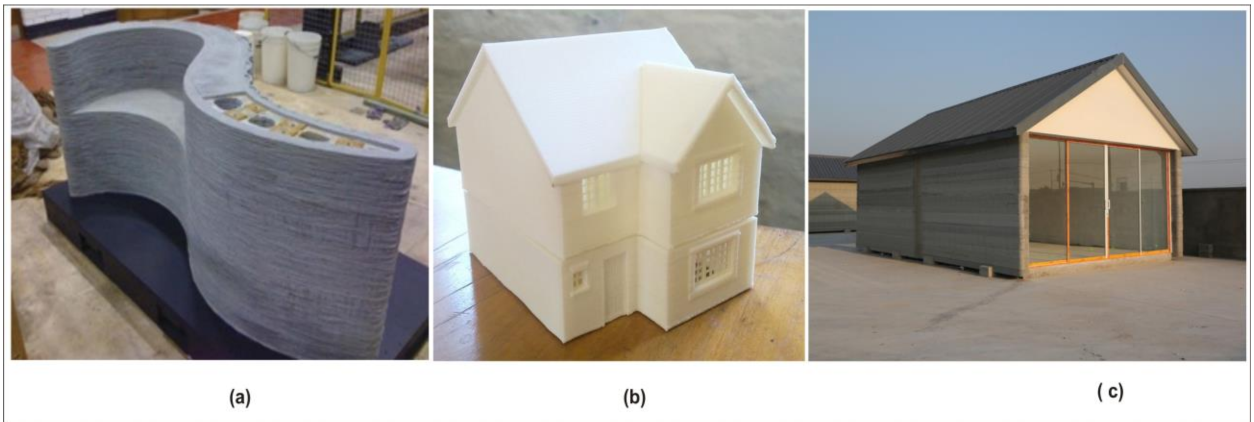


Figure 4. 12: Application of AM technology in the construction and building industry

Source: (a) 3ders.org, 2014 (b) Ard-Digital, 2015; (c) Dezeen. 2014.

4.2.8 Research and Development (R&D) Industry

Currently, AM technology is an exciting development in the education sector across the world. It is also referred to as an emerging technology that would revolutionize the colleges, universities, and high schools, and brings great possibilities to different educational disciplines ranging from Science, Engineering, Technology, Geography, Geology, Biology, Chemistry, Mathematics and Fine Art (Martin, 2013; Sculpteo, 2015). For an effective use of AM technology in the education sector, a non-competitive collaboration between AM companies (i.e. manufacturers of 3D printers, 3D printing service Bureau and manufactures of AM materials) and the education institutions such as (universities and research institutes) would play vital roles in developing industry standard, educational curriculum and in educating the industry workforce (QTR, 2015).

Research and development is a promising field where AM/3D printing technology is influencing the industry and education sector. On a yearly basis, more countries such as (United States, Germany, China, United Kingdom, Spain, Australia, Singapore, and as well as South Africa) research councils/institutes and organisations such as (PWC, Amazon, Deloitte, HP, General and Electric) are producing white papers, journals and documents showcasing the recent technological advances in the field of AM (Jürgen *et al.* 2013; Garth, 2016; 3Printr, 2016; De Beer *et al.,* 2016; Hague *et al*. 2016; Li *et al.* 2016). Munoz *et al.* (2013) also stated that "in North America and worldwide, governments and key industry initiatives are financially supporting advanced manufacturing and AM research". More so, some countries such as Canada, United States, China, Australia, South Africa and United Kingdom have national programs that support AM research at the university level (Munoz *et al.* 2013).

4.3 Risk and uncertainty, and other considerations within additive manufacturing

Despites the tremendous advances within AM field, there are still numerous challenges, risks, uncertainties and barriers necessary to be addressed before this disruptive technology can reach its full potentials. However, new technology always comes with different challenges at the infant stage, which is quite the same with AM technology. Some of the risks, uncertainties and barriers associated with AM technology are "quality control, uncertain products liability, intellectual property, environmental hazard, standards development, data integrity and management, software and hardware usability" (Lloyd's Register, 2016).

Widmer and Rajan (2016) identifies intellectual property as one of AM technology challenges that needs to be addressed. For instance, when it comes to "intellectual property" issue with AM printed parts, it is very difficult for the original designer of the models/products/parts to preserve the original data file which requires a copyright law to be put in place (QTR, 2015). This area has generated a large number of questions, concerns and uncertainties; and in order to address this issue, intellectual property leaders (including the owners, makers and users of AM technology) needed to develop effective regulations that will reduce threat of dispute or litigation (Widmer and Rajan, 2016)

Another uncertainty of AM to be addressed is "Product Liability" because there is a need for collaboration and cooperation from the original manufacturer, third party manufacturer, retailer and end-users. At the moment, end-users find it very difficult to know if the product he/she is buying is from original manufacturer or third party or if the product meet the required specifications (Mayer-Brown, 2013; QTR, 2015). Environmental hazard is another issue with the AM industry because the AM material contains toxicity and chemical substances that spread into the atmosphere during production (AMO, 2012; QTR, 2015). In 2013, Robert Olson, a technology analyst, wrote an article on "the environmental forum" in relation to AM/3D printing. Robert Olson explains that **"**while 3D printing has a lot of potential, there are risks of overprinting of materials and production of toxic fumes from the plastic materials used in additive printing" (Olson, 2013; Rehman, 2014).

On the other hand, Rehman (2014) mentions some of the importance of AM technology over environmental hazard such as [zero waste of materials, potential for recycling, zero transportation energy, and lower carbon dioxide footprint) when compared to conventional manufacturing in term of environmental impact and hazard. It's believes that AM technology could be environmental-friendly despite the alarming environmental hazard issue such as energy (electricity used) and types of materials used. In term of various environmental related issues, Olson (2013) provides six green design principles as a suggestion for environmental hazard issue related AM technology. The suggestions are based on a proposal for an initial "*Green Design Framework for Additive Manufacturing and 3D printing technology"* as stated below:

- Development of an additive manufacturing processes that uses renewable and biodegradable materials efficiently.
- Energy and resource efficiency AM systems (3D printers) should be manufactured to allow waste prevention, durability improvement, and easy to repair and upgrade.
- To use materials that are easily recyclable and to ensure they are properly recycled.
- The manufacturers should design recyclable 3D printers

- For safety and healthy operation purposes, 3D printers that support non-toxic raw material should be designed and manufactured. That is, non-toxic raw materials that contains plastic substances such as polylactic acid (PLA) plastic and this will minimize exposure to toxic materials of different kinds.

- The manufacturers should provide easy to understand information for safe operation (i.e. consumer education) and this would be useful for the consumers of 3D printers thereby giving appropriate information on how to use the 3D printers safely and efficiently.

Standardization is also recognized as another challenge in the field of AM and recently, this has cut the attention of various research groups in AM globally to start responding to this critical issue. According to Scott *et al.* (2012) as cited by Ford (2014) developing standards is critical to increasing diffusion and adoption of AM technology. Standards serve as a foundation for designing and manufacturing a product which must conform to certain specifications and also to have a compatibility with products provided by various suppliers seeking the same quality, performance and interchangeability (Scott *et al.* 2012). Lots of issues are associated with AM standardization such as quality control techniques and increase in product certification. ASTM F432 committer on AM standardization was established in 2009 and the committee are working toward effective standardization procedures for AM technology and this is discussed extensively in section 5.5 of chapter 5.

4.4 Chapter summary

This chapter investigated various applications of additive manufacturing from a global perspective. The literature has shown that AM/3D printing are widely used and shows that the technology is still at an embryonic stage and lots of awareness still need to be done to promote the technology within the universities, research institutes and industries. Considering certain risk and uncertainty surrounding AM advancement, several countries and industries are very sceptical to implement AM systems in their organizations. For AM technology to be fully adopted, appropriate standardisation processes have to be developed to enhance quality control.

The next chapter presents the sustainability of additive manufacturing in the educational sector. The next chapter will consider the role of AM in improving resources efficiency and this next chapter addresses the need sustainability AM education by identifying sub-factors necessary for this such as university-industrial collaboration. Lastly, the chapter discuss the general standard for sustainability of AM as presented by ASTM F432 committer on AM and knowing these standards will influence the AM education and research activities at the universities worldwide.

Chapter 5

5. Sustainability of Additive Manufacturing in Education Sector

This chapter presents a review of various scientific papers, publications and journals on the sustainability of additive manufacturing in the educational sector. This chapter discusses the possible means of sustainability of AM education based on these factors: university-industry collaboration, technology transfer, education and teaching, and technology and research. The indicators for AM sustainability and the international standards for sustainability of AM were reviewed in this chapter.

5.1 Sustainability and Additive Manufacturing

As sustainability campaign or strategy is very important to every sector such as manufacturing industry, healthcare, banking and financing, production, engineering bodies, agriculture, information technology, telecommunication and engineering education, so also it is very crucial to additive manufacturing education as an educational curriculum at the university. This chapter is very relevant to this current study because sustainability is the key to the development of AM education and its curriculum for teaching and this allows the relevant stakeholders in STEM education to develop appropriate strategy/framework/roadmap that will lead toward effective sustainability of AM education at high schools, colleges, universities and research institutions, both now and in the future.

According to Malshe *et al.* (2015) the term sustainability is a varied conception in today's world and the concept of sustainability was largely motivated as a result of a series of environmental incidents and disasters, as well as fears from chemical contamination and resource depletion. Sustainability is not new for any area of industry, including additive manufacturing, and there are currently a number of ongoing research projects, both in industry and in academic institutions that are investigating sustainability, embedded carbon and research activities, which would need to be done in the future to move AM technologies towards sustainable mainstream production (Muthu and Savalani, 2016).

The emergence of advanced manufacturing technologies such as AM has sustainability advantages and disadvantages in term of materials, environmental impacts, cost of production and supply chains. According to Ford and Despeisse (2016) the consequences of adopting AM technology on industrial sustainability are not well understood. Ford and Despeisse (2016) conducted an exploratory study based on the publically available data to provide insights into the impacts of AM on sustainability. Benefits are found to exist across the product and material life cycles through product and process redesign, improvements to material input processing, make-to-order component and product manufacturing, and closing the loop. As an immature technology, there are substantial challenges to these benefits being realised at each stage of the life cycle. Ford and Despeisse (2016) summarises these advantages and challenges; and discusses the implications of AM on sustainability in terms of the sources of innovation, business models, and the configuration of value chains.

According to Hao *et al.* (2010) AM technology enables the rapid development of sustainable products and the technology is increasingly used for manufacturing of lightweight components or parts which allows industries and companies to save cost and materials, most especially to save a considerable amount of material, energy consumption and production cost of one-off or medium products production. AM technology allows *non-processed raw materials to be recycled and re-used* by AM machines and thereby reducing material waste drastically (Hao *et al.* 2010).

Malshe *et al.* (2015) maintain that with the growing interest in the area of AM technologies, great concerns have arisen as regarding the relative performance of these AM technologies processes as compared to conventional or traditional techniques when seeing from an economic, environmental, and social perspective. Malshe *et al.* (2015) explain that sustainability-related advantages can be realized through AM and the technology is often promoted as a sustainable technology, which is appropriate for both future development and application. Despite the fact that AM is recognised as a sustainable technology, it is also important to understand the relative costs, environmental impacts and the human health effects of processes and materials of this technology (Malshe *et al.* 2015).

Liu *et al.* (2016) critically reviewed the environmental impact of AM/3D printing technology from a qualitative and quantitative approach, which allows them to provide a comprehensive understanding of AM/3D printing technology for the public and future researchers. Liu *et al.* (2016) recognize that AM technology as an *efficient and sustainable technology in the fields of advanced manufacturing*. According to Liu *et al.* (2016) in recent years, a considerable number of studies, including basic theoretical research, technology innovation and industries application have been conducted in order to progressive research in AM technology which allows a better performance in advanced manufacturing. However, the benefits of AM from an environmental perspective are still yet to be seen and its sustainability is still yet unknown (Liu *et al.* 2016). Therefore, Liu *et al.*'s (2016) study proposes a new framework for AM processes sustainability assessment and improvement by integrating the product Computer Aided Design (CAD) and Life Cycle Assessment (LCA).

5.2 Advantages of additive manufacturing sustainability

Despeisse *et al.* (2015) describe AM as a technology that offers a great potential of providing a number of sustainability advantages. A number of literature (Chen *et al.* 2015; Mani *et al.* 2014; Despeisse *et al.* 2015; Despeisse and Ford, 2015) have shown the advantages of the AM technology sustainability which includes: generation of lower waste materials during manufacturing or production life cycle, designing and optimization of complex geometrics designs, manufacturing of lightweight components thereby reducing material consumption and energy consumption during production phase, reduction of environmental impacts that are associated with transportation in the supply chain, manufacturing of spare parts or components on demand which leads to reduction in inventory waste.

AM allows freedom of design and this implies that products and components can be redesigned and meeting the design's requirement. More so, AM has reduced manufacturing and supply chain complexity (Despeisse *et al.* 2015). Hardcastle (2015) states that AM technology allows manufactures and designers to make structures using lighter materials that are not possible to make using traditional methods. For instance, within the aerospace industry, a 3D-printed titanium bracket of an (Airbus) aircraft was produced, and this makes the aircraft more economical to operate; and it reduces fuel consumption and lowers CO2 emissions This new development in the aerospace industry has shown that AM can be considered as a sustainable technology. Airbus group of companies is a global leader in aeronautics business.

5.3 Sustainability of additive manufacturing in education

Huang and Leu (2014) provides a comprehensive report of the United States National Science Foundation (i.e. the NSF 2013); an AM workshop on *"Frontiers of Additive Manufacturing Research and Education"*. Various stakeholders from academia, industry and government were present to share their ideas, innovations and knowledge as relating to the frontiers of AM research, education, and technology transfer. Huang and Leu (2014) report summarizes the current state, future potential, gaps and needs for AM and more so, recommendations were made for AM education sustainability based on four factors which will be considered later in this section of this chapter.

From an education and training perspective, AM has a great potential and capability to promote science, technology, engineering and mathematics (STEM) education and through this medium a wide population of students and adults can be engaged from both formal and informal settings. In the United States of America, AM education and training has begun to play a significant role in promoting and establishing a healthy engineering education ecosystem in most U.S universities and colleges (Huang and Leu, 2014).

To further enhance the sustainability of AM education and training at the universities and colleges, the following four factors (***university-industry collaboration, technology transfer, education and training, and technology and research***) needed to be taken into full consideration as stated in (Huang and Leu, 2014) report as follows:

5.3.1 University-industry collaboration and technology transfer

The beginnings of AM are firmly embedded in engineering, precisely within the industry and manufacturing sectors, where the research and development of new products are being carried out (Huston *et al.*, 2015). According to Bak (2003) as cited by (Huston *et al.*, 2015) the material variety and high-quality products that can be produced by current generation AM machines or 3D printers is allowing industry to move from rapid prototyping to AM production and based on this reason, AM/3D printing technology skills have become a central skill sets for students studying engineering and technology related degrees.

Huang and Leu (2014) describe AM as a technology that has recently experienced a significant growth but still not widely accepted by most industries across the world. Huang and Leu (2014) stress that "in the next few years, it will be critical to improve the technology to the point of changing people's mind-set and gaining industry acceptance, and to broaden, develop, and identify manufacturing applications that are greatly improved due to or are only possible with AM processes. This will lead to a substantial growth in university-industry research and collaboration.

There is a need for university-industry collaboration on AM education and technology transfer. Technology transfer will fill the technological gap between the theoretical and practical knowledge of AM technology. Another important aspect of university-industry collaboration is that it will enhance and revolutionize the university students, academics, and industry professionals experience and it will create a sustainable competitive edge for the students and the university in term of research AM.

5.3.2 Education and training

According to Bourell *et al.* (2009) as cited by (Hart and Go, 2015) as early as 2009, it was identified that AM education is critical to the advancement of the AM field, and that educational programs in AM should be implemented at the university, industry, technical colleges and management institutions. Moreover, the rapid growth and disruptive potential of AM technologies demands that educational programs that addresses the fundamental principles of AM should be introduced into the educational sector, which will enable designers and engineers to gain hands-on experience of AM (Hart and Go, 2015).

To achieve sustainability of AM in this regard, educational programmes should be paramount at all levels - high schools, colleges and universities to prepare students for jobs or workforce in AM and manufacturing industry. In industry, education and training programmes should be tailored for industry engineers and professionals within product design and manufacturing system sectors, and this will enable them to use their AM technology knowledge and skills to complement the existing traditional manufacturing system because AM cannot replace traditional manufacturing technique but rather complement. The government also need to invest more in the advancement of AM technology, most especially in both education and research, and this will greatly assist in the sustainability of AM education.

5.3.3 Technology and research

The growth of any new technology requires a continuous research activities and effective adoption of the technology both in industry and academic institutions. This also applies to AM technology because the technology is still new and has not been widely accepted by many industries and universities worldwide. However, the technology is gaining the attention of the several industries and universities daily, which shows that the future of AM technology is very brighter. Despite diverse technological advances in AM technology in recent years, many challenges are still unaddressed, for instance limitation of materials for use of AM processes, inadequate repeatability and consistency in manufacturing of parts, need of qualification and certification methodologies for AM processes and poor parts accuracy (Huang and Leu, 2014).

Based on the NSF workshop report by Huang and Leu (2014), during the presentation and discussion sessions, some vital recommendations were made for the AM technology and research. During the discussion sessions of the workshop, the AM experts and attendees identifies the gaps and needs for AM technology and research. More so, four AM technology elements and system integration research areas were addressed and suggested as shown in Figure

5.1, namely: materials development and evaluation; design methodology and standards; modelling, monitoring, control, and processes; characterization and certification; and system integration and cyber implementation (Huang and Leu, 2014). For sustainability to happen in term of technology and research, there is a need for wide adoption AM across research institutions (Huang and Leu, 2014).

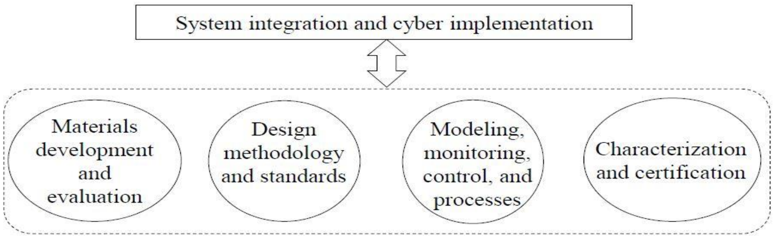


Figure 5. 1: Additive manufacturing technology elements and system integration research areas

Source: Huang and Leu (2014),

5.4 Indicators for additive manufacturing sustainability

The essence of this section on the 'Indicator for Sustainability in Additive Manufacturing' is to consider the necessary indicators that could lead to the sustainability of additive manufacturing technology in general. This implies that sustainability of AM technology itself will also lead to the sustainability of AM technology within the educational sector if rightful indicators are put in place. Therefore, it is very crucial to identify major indices that could influence further development, growth and sustainability of AM technology both in the industry and academia.

Studies by (Kellens, *et al.* 2014; Le Bourhis *et al.* 2013; Le Bourhis *et al.* 2014) have shown that "a comprehensive analysis of sustainability must be considered in every step of the product life cycle, ranging from the raw materials to disposal at the end of product life, including manufacturing stages when quantities of materials and energy are consumed" (Fratila and Rotaru, 2017). According to Fratila and Rotaru (2017) AM processes must demonstrate their environmental-friendly capability considering the following sustainability principles, namely: efficient use of material and energy consumption, industrial waste management, low cost of manufacturing production, avoidance of toxic emissions and materials, issues relating to health and safety, low environmental impacts, personnel health improvement, safety, economic efficiency, reparability, reusability, recyclability and disposability of the products manufactured using AM technologies (Fratila and Rotaru, 2017).

According to Salonitis (2016) there is a need for a number of metrics to be used for assessing the performance of a process with regard to its implications for sustainability. Chen *et al.* (2015) conducted a research on sustainability related implications whereby they made a comparison between existing manufacturing technologies and additive manufacturing technologies. Their findings show the implications of AM on sustainability from three perspectives, namely, *economic, environmental and social dimensions of sustainability*, and it is very evident that both environmental and economic dimension of sustainability are closely related (Chen *et al.*, 2015).

From an economic dimension of sustainability, AM technology has significant economic potential. For instance, AM allows manufacturing to be decentralized, many individuals who are not necessarily manufacturing or design experts have direct access to information and design, and manufacturing democratisation. The energy efficiency of the AM processes has a direct impact on the economic because the energy cost is very significant (Salonitis, 2016). More so, the environmental dimension of sustainability of AM processes can be approached using three major indices, namely: the total environmental impact, the CO_2 emissions and the energy source. The life-cycle analysis (LCA) is usually used to assess the environmental impact of the manufacturing processes (Salonitis, 2016). The literature has shown that AM processes perform better than the existing manufacturing technologies when LCA was used to assess the manufacturing processes (Serres *et al.*, 2011).

Kai *et al.* (2016) study also supports (Salonitis, 2016) study on AM sustainability indicators based on economic, environmental and social indicators. Kai *et al.* (2016) explain that the indicators to measure AM sustainability are few extensive, inconsistent and uncorrelated. Kai *et al.* (2016) argues that the metrics for measuring AM should be more focused on the performance and sustainable manufacturing that actually comply with demonstrating the reality. From literature, some of the metrics found are more on economic indicators which look at AM technology from product, manufacturing and supply chain perspectives.

Some studies compare AM technologies with traditional manufacturing, but the economic indicators have clear advantages as against the traditional manufacturing disadvantages. However, from the economic perspective, the indicator shows that AM technologies have not been regarded as *sustainable manufacturing yet* (Kai *et al.* 2016). The environmental indicators on the other hand, shows more reality, that is, reduction on material waste, raw materials consumption and consumption of energy. The environmental indicator is more specific and shows the green benefits to the corporate image or organization. The social indicators are not as addressed in a manufacturing vision, and certainly this involves the health and safety of those working directly with AM technology (Kai *et al.* 2016).

Reviewing the concept of sustainability in manufacturing, it shows that sustainability has increasingly become a main topic for discussion across different research fields or groups. From the academic environment, research can be found in the most diverse areas relating to sustainability (Mançanares *et al.* 2015). Gunasekaran and Spalanzani (2012) proposed a framework to analyse sustainability from a manufacturing perspective and the framework is based on seven primary issues, namely: (1) Manufacturing sustainability challenges and opportunities; (2) Sustainability in business processes; (3) Sustainability in product development; (4) Sustainability in the supply chain; (5) Sustainability in production operations; (6) Sustainability in the distribution chain; and (7) Sustainability by remanufacture, recycling and reverse logistics (Mançanares, *et al.* 2015).

Gunasekaran and Spalanzani (2012) conducts more research on the sustainability challenges in AM which led to the construction of a structured analysis of the AM field through the use of a proposed framework by Gunasekaran and Spalanzani (2012) where sustainability in manufacturing was analysed. Gunasekaran and Spalanzani (2012) adapted same proposed framework for “Sustainability in Manufacturing” to “Sustainability in Additive Manufacturing” as shown in Figure 5.2. Gunasekaran and Spalanzani (2012) proposed framework for AM is considered robust in analysing a novel manufacturing technology such as AM (Mançanares, *et al.* 2015). The framework is based on the seven main subject matters mentioned above on sustainability in manufacturing as earlier highlighted in the previous paragraph.

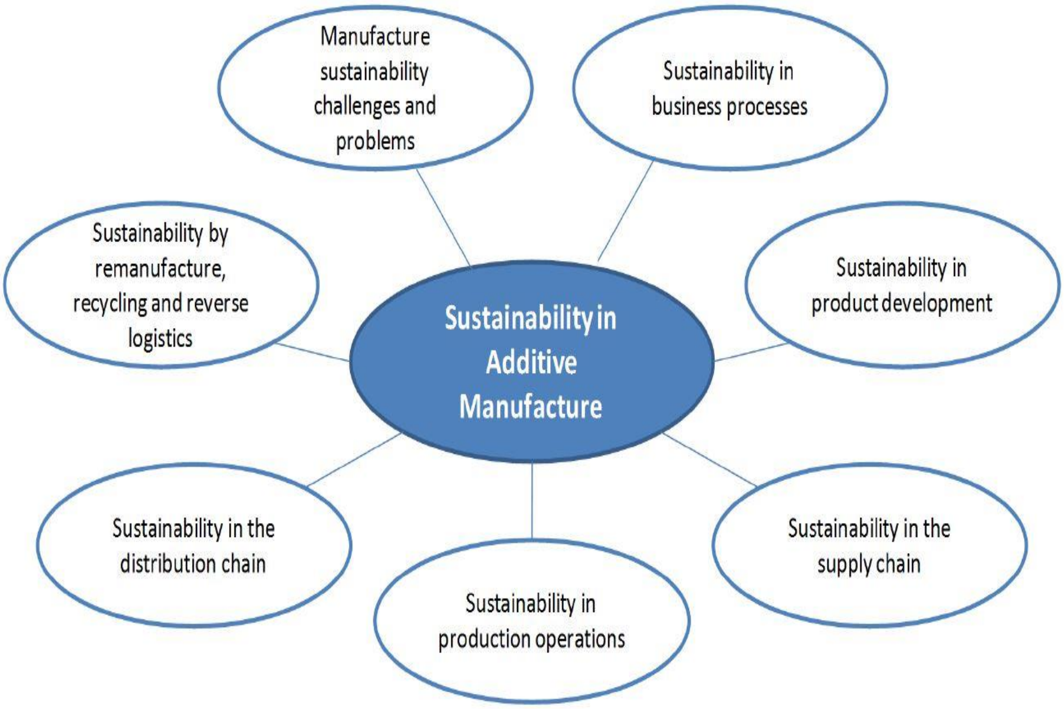


Figure 5. 2: Proposed framework for sustainability in Additive Manufacturing field.
Source: Mançanares, *et al.* 2015; Gunasekaran and Spalanzani (2012).

5.5 International standards for sustainability of additive manufacturing

Standardization is very important to the future of additive manufacturing and also AM education, because standards are part of the necessary evolution of new or emerging technology (Stratasys, 2015). Adoption of a novel technology for end-user components/parts need a certain level of standardization which had not been part of the early additive manufacturing/rapid prototyping movement. It is known that "Standards allow engineers to design to a known set of parameters and build a level of trust in the fulfilment and manufacturing process" (Stratasys, 2015). At present, almost all the major companies or organisations using AM technology for end-use components/parts production creates their own set of AM/3D printing materials and processing guidelines (Stratasys, 2015).

For AM sustainability, ASTM international, a global leader in the development of standards in 2009 established a Committee F42 on Additive Manufacturing Technologies and the aim of this committee F42 is to promote knowledge, assist to stimulate research and encourage the implementation of AM technologies (ASTM, 2017). The Association of German Engineers worked on a series of guidelines for ASTM standard which was called "rapid technologies", and eventually these guidelines led to the creation of ISO/TC 261 in 2011 (Tranchard and Rojas, 2015).

According to Naden (2016) the ISO/TC 261 and ASTM F42 international have jointly developed the Additive Manufacturing Standards Development as shown in Figure 5.3, it is a framework which will help meet the needs for new technical standards in the fast-growing field of AM. Naden (2016) maintains that the new standards structure does not enclose the scope of work for any standards organisation, but it gives a framework in which most of the standards needs can be met. ISO/TC 261 and ASTM F42 international also developed a companion guidance document to accompany the structure (Naden, 2016). Therefore, for sustainability of AM technology, Figure 5.3 shows the agreed-upon additive manufacturing standards structure developments.

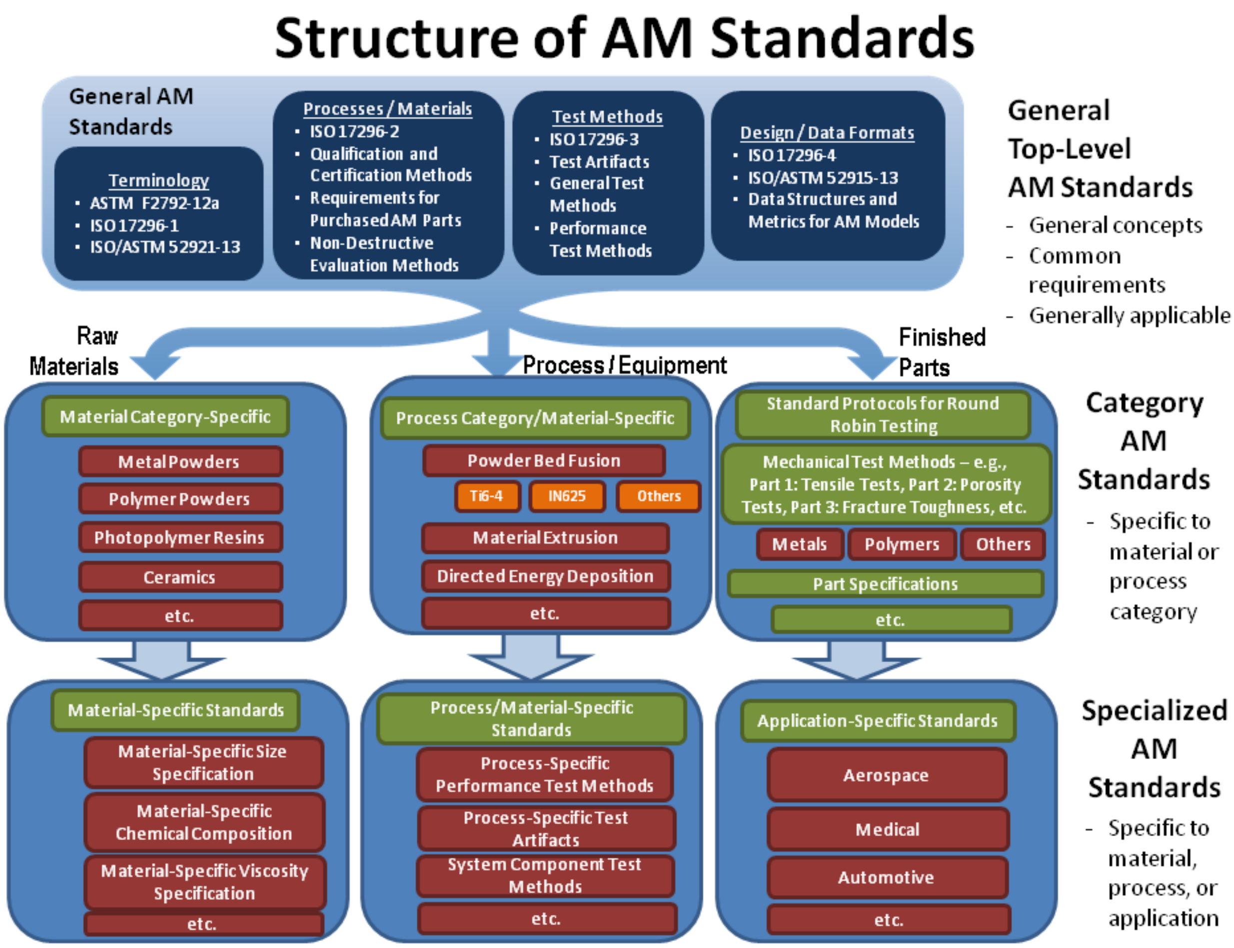


Figure 5. 3: The agreed-upon common structure of AM standards development.

Source: Lenz (2015); ISO/TC 261 and ASTM F42, version 2 (2013).

This section on the "International Standards for Sustainability of Additive Manufacturing" is necessary in this chapter and has an important role to play in the development of an effective AM education curriculum at the university level, for instance, as part of the proposed AM education curriculum presented in section 8.1.3.1 of chapter 8 by the researcher; and a topic title - "Structure of AM technology standards" was listed among the topics for AM course at the university and it believes that the topic will broaden the knowledge of students and the importance of standardization in AM technology. In addition, it believes that good understanding of AM standards will increase the credibility of research activities within the AM research group at different universities globally.

5.6 Chapter summary

Firstly, this chapter has reviewed the concept of sustainability based on the conception in today's world. Different studies have considered additive manufacturing as one of the emerging advanced manufacturing technologies that have both sustainability advantages and challenges. Papers reviewed indicates that AM education has great potential and capability to promote STEM education. Some of the crucial ways to further promote the sustainability of AM education at the university can be categorized into - *University-industry collaboration, technology transfer, education and training, and technology and research.* This chapter also identified indicators for AM sustainability based on three vital factors, namely, economic sustainability indicator, environmental sustainability indicator and social sustainability indicator.

The next chapter presents the research methodology, both the empirical investigations and findings. The theory behind scientific methods and more focus is on quantitative research approach. The next chapter will also discuss each step involved in the research methodology. The measuring instrument (questionnaire) will be clearly discussed and certain data analysis and statistical terminology relevant to the study will be presented.

Chapter 6

6. Research Methodology

This chapter presents the empirical investigation of the study. The empirical investigation addresses the theory behind empirical investigation, scientific method, and quality of questionnaire survey. The different phases involved in the research methodology are clearly explained. This chapter presents the empirical findings; the measuring instrument explained and some useful statistical terminologies relevant to the study were presented as well.

6.1 An Overview of Empirical Investigation

An empirical investigation research approach is a kind of research that is based on experimentation or observation, that is, evidence. For instance, empirical research is usually conducted to answer a specific research question or for hypothesis testing (UNCC, 2017). According to Isaac and Micheal (1997) as cited by (Vosloo, 2014) an empirical investigation involves a planned process of collecting and analysing data; in a way that is systematic, purposeful and accountable. Currently, in the world of research, there are three major research methodologies which have spanned across different research fields, from social sciences, education, medical to engineering. This research methodology includes qualitative, quantitative and mixed methods.

In this study, an empirical investigation was undertaken using *quantitative research approach* to obtain a reliable and valid data which is in accordance with the research questions and the aim of the research, and this will further strengthen the trustworthiness and validity of the research.

6.1.1 An overview of exploratory research approach

An exploratory research approach is a type of research conducted concerning a research problem where there are little or no prior research to refer to. Exploratory research usually focuses on gaining insights and familiarity for future investigation or undertaken when problems are in an initial phase of investigation (Eugene and Lynn, 2017). According to Van Wyk (2011) the main aim of exploratory research is to discover the boundaries of the environment in which the research problem, opportunities or situations of interest are possibly to reside, and to pinpoint the salient factors or variables that might be found there and where it could be of relevant to the studies.

This type of research approach can be characterized by a high degree of flexibility and it has no formal structure (Van Wyk, 2011). An exploratory research approach is most suitable for a research design for those projects that addresses a subject where there are high levels of uncertainty and ignorance about the topic and also exploratory research is more appropriate when the research problem is not well understood, for instance, a situation whereby there are few existing studies on the topic (Van Wyk, 2011).

Exploratory research determines the feasibility of future research in the topic area, and it is often used to generate formal hypotheses and develop more accurate research problems, and it helps to establish research priorities. One of the disadvantages of exploratory studies usually is using small sample sizes and the results are not generalizable to the population as a whole and it generates information and interpretation that is subjected to bias. Also, exploratory studies do not aim at providing the final or conclusive answers to the research questions, but just to explore the research topic with varying levels of depth (Dudovskiy, 2016). Most common methods of exploratory research approach are: *Literature survey, focus groups, interviews, and case analyses.*

6.1.2 Descriptive research approach

Knupfer and McLellan (1996) describes a descriptive research approach as a type of research that does not fit neatly into the definition of either qualitative or quantitative research methodologies, however, descriptive research utilizes the elements of both qualitative and quantitative methodologies usually with the same study. The term “descriptive research” introduces the types of research questions, design and data analysis that would apply to a given research topic (Knupfer and McLellan, 1996). A descriptive research approach can be either qualitative or quantitative, and it might involve collections of quantitative information which could be tabulated along a continuum in numerical form, for instance, a descriptive research can describe categories of information like gender or patterns of interaction when using technology in a group situation.

More so, descriptive research requires collecting data that represents events and then organizes, tabulates, depicts, and describes the data collection (Glass and Hopkins, 1984; Knupfer and McLellan, 1996). It was reported that majority of quantitative research falls into two areas, firstly, a study that describes events and secondly, a study aimed at discovering inferences or friendly/casual relationships. Descriptive research focuses on finding out “what is”, that is, observational approach and mostly survey methods are been used to collect descriptive data (Borg and Gall, 1989).

Descriptive research approach details the summary of data such as measures of central tendency, which includes “the mean, median, mode, deviance from mean, variation, percentage and correlation between variables” and most survey research comprises the measures of central tendency but most times, there is a need to go beyond the descriptive statistics, so that inferences can be drawn (Knupfer and McLellan, 1996). Therefore, descriptive statistics make use of data collection and analysis techniques that produces report about the *measures of central tendency, variation and correlation*. It is observed that the combination of descriptive statistics and correlational statistics which allows them to focus on specific types of research questions, methods and outcomes is what distinguishes descriptive studies or research from some other types of research (Knupfer and McLellan, 1996).

6.2. Quantitative research method

A quantitative research method focuses on describing a phenomenon across a larger sampling size of participants which provides the possibility to summarize the characteristics across groups or relationships (Ben-Eliyahu, 2014). A quantitative research method quantifies the problem by mean of generating numerical data and transforming the data into usable statistics. This type of research method can be used to measure attitudes, behaviours, opinions and some other defined variables. The result can be generalized from a larger sample population. (Wyse, 2011). Quantitative research method emphasizes objective measurement and the statistical, mathematical or numerical analysis of data collected through polls, questionnaires and surveys (Babbie, 2010; Muijs, 2010, USCLibraries, 2017). It might also be through manipulation of pre-existing statistical data using computational techniques.

Quantitative research method centre on collecting numerical data and generalizing it across groups of individuals and can also be used to explain a specific phenomenon (Babbie, 2010; Muijs, 2010, USCLibraries, 2017). Quantitative research data collection can be conducted using the following methods, namely, *face-to-face interview, telephone interview, longitudinal studies, website interceptors, online surveys, paper surveys (self-administered), online polls and systematic observations* (Wyse, 2011). According to Sukamolson, (2007) there are various types of quantitative research, it can be classified to: Survey Research; Correlational Research; Experimental Research, and Casual-Comparative Research.

6.3 An Overview of the Research Methodology

A research methodology describes the research methods, the appropriate approaches and designs being used throughout the research. Kallet (2004) describes a research methodology as "an action to be taken to investigate a research problem and the rationale for the application of specific procedures or techniques used to identify, select, process, and analyse information applied to understanding the problem, thereby, allowing the reader to critically evaluate a study's overall validity and reliability". A research methodology section of a research answers two most important questions, firstly, how was the data collected or generated? And secondly, how was it analysed? This section of a research must be direct, precise and at all times written in past tense (Kallet, 2004; USCLibraries, 2017). Figure 6.1 shows the research methodology designed for this research, it comprises of solid 12 steps and each step are briefly explained below.

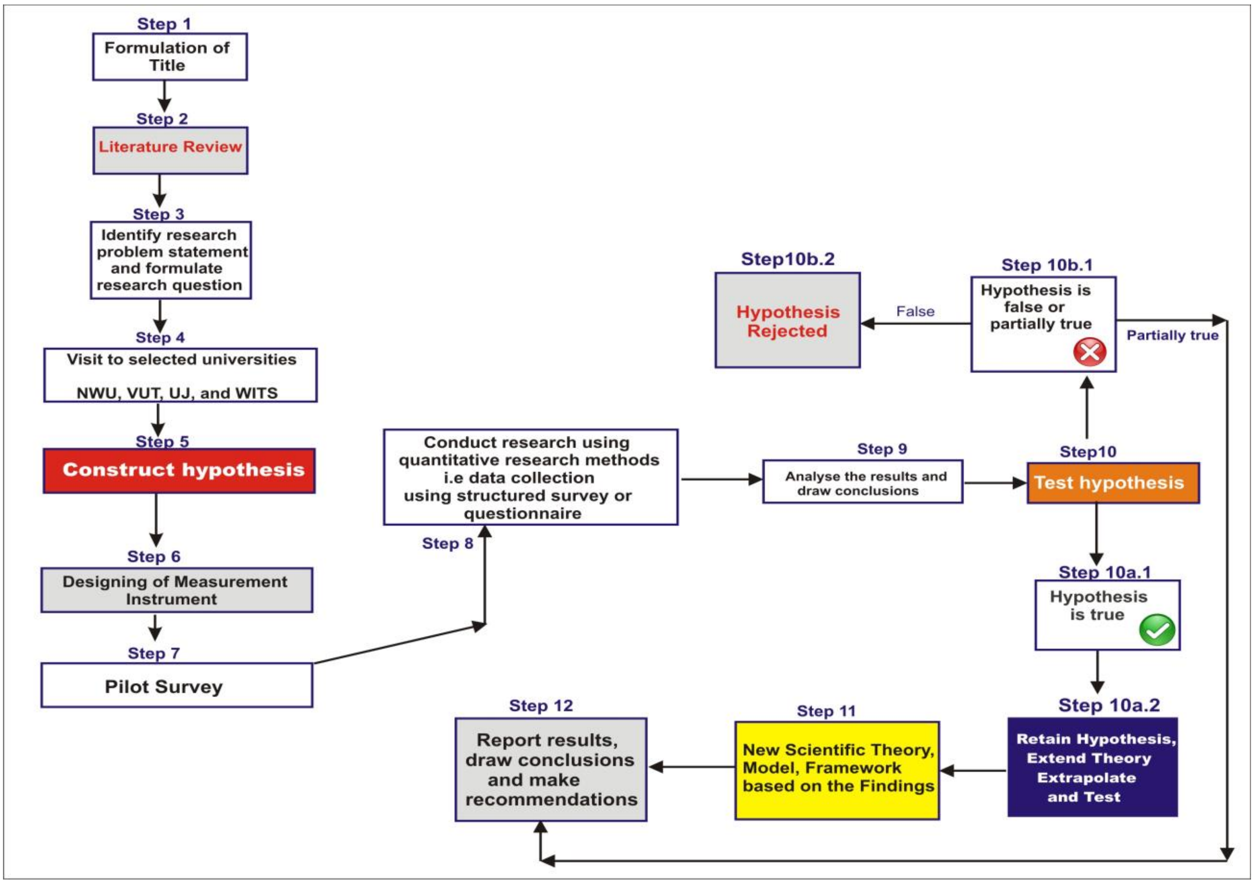


Figure 6. 1: Research Design/Methodology.

Source: Researcher's own construction

- **Step 1 – Formulation of research title**

The most basic and important aspect of a research paper is the "title" and a good research title must condense the paper's content in a few words, capture the readers' attention and differentiate the paper from other papers in the same subject area (Kulkarni, 2013). Bavdekar (2016) also describes a research title as the gateway to the contents of a scientific article and this is the first part of the manuscript that the editors or reviewers read. Based on the title of research, a reader can judge if a particular research paper is relevant to the current study under investigation or not. Therefore, after several considerations and literature reviews, a research title was formulated for this study as "*Framework for effective Additive Manufacturing education at South African universities*".

- **Step 2 – Literature review**

Taylor (2017) describes a literature review as an account of what has been published on a particular topic or research area by an accredited scholars and researchers. The purpose of literature review is to convey to the readers or other researchers what knowledge and ideas have been established in that research area or subject and it must be guided by the research objectives, problem or questions (Taylor, 2017). This current doctoral study conducted a comprehensive literature review as relating to the title of the research.

The literature reviews cover additive manufacturing technology in general with more emphasis on the various AM technologies and its applications in the education sectors. The literature review also covers various applications additive manufacturing across different industry and the sustainability of additive manufacturing most especially in the educational sectors i.e. universities. The literature also addresses the importance of standardization in AM education.

- **Step 3 – Identification of research problem and formulation of research questions**

Bryman (2007) states that "a research problem is a definite or clear expression i.e. statement about an area of concern, a condition to be improved upon, a difficulty to be eliminated, or a troubling question that exists in scholarly literature, in theory, or within existing practice that points to a need for meaningful understanding and deliberate investigation". A research question is also one of the critical steps in any research process, and must be clear, and the questions have to summarize the exact problem the researcher is investigating. A research question could start by asking an open-ended question such as "how" or "why". In this study, several sources of literature were reviewed from accredited open scientific journals or databases and the research problem was identified and a concise research questions were formulated as well.

- **Step 4 – Visit to selected universities**

In order to proceed on this study, the researcher visited Vaal University of Technology [Idea 2 Product (I2P)] Lab both on the Main and Sebokeng campus prior to the data collection phase of the research, and the researcher also did three months' research internship at the VUT *Additive Manufacturing Unit* at Sebokeng campus that provided the researcher with hands-on experience of both high-end industrial grade AM machines and entry-level FDM desktop 3D printers at the I2P Lab. The researcher also visited 'NWU Pukke 3D Printing Centre' to access their campus facilities at the School of Mechanical and Nuclear Engineering on the Potchefstroom campus and the staff were able to introduce the researcher to the facilities and provide some insights on their current research and students' involvement in their laboratory.

- **Step 5 – Formulating of hypotheses**

According to Creswell (1994) "hypothesis is a formal statement that presents the expected relationship between an independent and dependent variable". Hypothesis usually follows four important steps which include: Stating the hypothesis as either null or alternative; setting the criteria for decision; collecting the data and evaluate the null hypothesis (Prasad *et al.*, 2001). Basically, the formulation of a research hypothesis varies and depends on the types of research studies a researcher trying to conduct either qualitative or quantitative.

A good research hypothesis must be testable (verifiable or falsifiable); and must not contain moral or ethical questions; and must neither too specific nor general; should be a prediction of consequences and considered valuable even when proven false (Prasad *et al.*, 2001). For the purpose of this research, certain hypotheses were formulated as specified in section 7.9 of Chapter 7.

- **Step 6 – Design of research measuring instruments**

One of the most important tools in any research is the measuring instrument, and which have to be carefully formulated and designed. The main purpose of a research measuring instrument is for data collection. This can be achieved using questionnaires (either structured or unstructured), interviews, observations and literature through journals. For the purpose of this study, both closed ended questionnaire and open-ended questionnaire were used for the data collection. After several literature reviews, the researcher was able to design the measuring instrument (a questionnaire). The questionnaire was sent to the statistical consultant at the North-West University Statistical Consultation Services and the questionnaire was validated i.e. face validation and some feedback was provided by the consultant.

The statistical consultant recommended that some of the questions should be removed, split or rephrased/reconstructed. was requested that the questionnaire be given to a language editor for proper proofreading of the entire questionnaire and make corrections where needed. The statistical consultant requested that an exploratory qualitative investigation (like - pilot survey) should be carried out before proceeding on the final data collection. Below is the response from the statistical consultant.

"I recommend an exploratory qualitative investigation. This entails requesting people similar to the expected respondents as well as peers to review the questionnaire and provide you with suggestion as to how you can improve it".

- **Step 7 – Pilot survey**

According to Hassan (2006) a pilot study can be defined as a "small study to test research protocols, data collection instruments, sample recruitment strategies, and other research techniques in preparation for a larger study". A pilot study is one of the very important stages in a research project and it is conducted basically to identify potential problem areas and deficiencies in the research measuring instruments and protocol before implementation during the main study or data collection (Lancaster *et al.,* 2004; Hassan, 2006).

For this study, the questionnaire used for the pilot study was converted from a hardcopy version to an online survey questionnaire using google form. The researcher sent the questionnaires via email to 25 people comprising academia, postgraduate students, post-doctoral fellow and industry expert in AM/3D printing technology to assist in completing the questionnaire and to provide feedback on how to improve the questionnaire if need be. It took two weeks for the pilot survey exercise and 11 people responded to the pilot survey as presented in appendix H. After the pilot survey, the questionnaire was amended, that is, some of the questions were reconstructed, some were removed completely, and new questions were added.

The question arises that how can a researcher figure out the appropriate sample size for a pilot survey, in term of minimum and maximum size. Connelly (2008) suggests that a pilot study sample should be 10% of the sample projected for the larger or main study. However, Isaac and

Michael (1995) and Hill (1998) suggested that 10 to 30 participants are good for a pilot study in a survey research.

- **Step 8 – Data collection**

Data collection in research can be described as "the process of gathering and measuring information on variables of interest, in an established systematic fashion that enables one to answer stated research questions, test hypotheses, and evaluate outcomes" (NIU, 2005). The questionnaire was circulated in a controlled manner through a self-administered approach to 200 participants which comprised undergraduate and postgraduate students; and few academic staffs (i.e. lecturers) and AM lab technicians. The target audience for the survey were primarily students who have access to additive manufacturing machines or have used AM/3D printing lab or facilities on their campuses.

- **Step 9 – Analysis and interpretation of the result**

The data collected was collated and forwarded to the North-West University (NWU) Statistical Consultation Services for further statistical analysis i.e. the closed–ended questions (structured questionnaire) and SPSS statistical software tool was used for the analysis, while the opened-ended questions were being analysed by the researcher which was based on the selected factors from the closed-ended questions. The NWU Statistical Consultation Services returned the statistical analysis in an excel files. For clarification purposes, in this study, the NWU Statistical Consultation Services ONLY carried out the statistical analysis of the data and the researcher studied the entire data analysis, carried out the discussion and interpretation of the data as documented in Chapter 7.

- **Step 10 – Hypothesis Testing**

According to Banerjee *et al.* (2009) "Hypothesis testing is an important activity of empirical research and a well worked up hypothesis is half the answer to the research question". Hypothesis testing would require both the knowledge of the subject or research area derived from a comprehensive review of the different literature and a good knowledge of basic statistical concepts are desirable (Banerjee, 2009). The main purpose of testing statistical significance, hypotheses are categorized by the method they defined the expected difference between the study groups (Banerjee, 2009). It could either be a null hypothesis (accept) or alternative hypothesis (reject). Hypothesis testing could be based on effect size, one and two tailed alternative hypotheses. The hypothesis for this study would be stated in Chapter 7.

- **Step 11 – Develop a new scientific theory or framework**

According to Nilsen (2015) and Sabatier (2007) “A framework usually denotes a structure, overview, outline, system or plan consisting of various descriptive categories, e.g. concepts, constructs or variables, and the relations between them that are presumed to account for a phenomenon”. Frankfort-Nachmias and Nachmias (1996) explained that a framework does not provide explanations; but only describe empirical phenomena by fitting them into a set of categories. Mostly, a scientific theory can be described as a set of analytical principles or statements designed to structure our observation, understanding and explanation of the world (Frankfort-Nachmias and Nachmias, 1996; Carpiano, 2006).

In this study, the literature outcome of the data analysis and interpretation assists the researcher to develop a new framework for effective AM education at South African universities.

- **Step 12 – Conclusions and recommendations**

The interpretation of the data analysis which was done with distinct reference to the selected South African universities; provides the researcher with the ability to complete this chapter of the research. The conclusions and recommendations are an important aspect of a research project whereby the researcher brought the entire research to a logical conclusion. This phase of the research would present the conclusions, significant contribution to knowledge and recommendation for possible future study in this area.

6.5 Overview of the questionnaire

A questionnaire is a research instrument which consists of a series of questions and other prompts for the purpose of gathering information from respondents. (CTI Review 2016). A questionnaire would allow the researcher to collect the most complete and accurate data in a logical flow. This is achieved with the aim to reach reliable conclusions from what the researcher is planning to observe. A well-designed questionnaire would meet the research aim and objectives, and thereby minimizing the unanswered questions (Abawi, 2013). The researcher needs to choose the appropriate methods of reaching the target respondents or audience which must be included in the questionnaire design process.

There are four most used methods of conducting a survey research as stated by (Crawford, 1997): [personal interviews, group or focus interviews, mailed questionnaires, telephone interviews]. Crawford (1997) highlights nine steps involved in the designing and development of a good questionnaire for research purpose as listed below:

- Decide the information required
- The target respondents or audience have to be defined
- The method(s) to reach the target respondents must be chosen
- Decide the content of the questions
- Develop the question wording
- The questions have to be put in a meaningful order and format
- The length of the questionnaire has to be checked
- The questionnaire has to be pre-tested i.e. conduct a pilot survey
- Develop the final survey form/final questionnaire.

A questionnaire can also be referred to as a multi-step process and it allows data collection of both subjective and objective data for large sample of the study population in order to have results that would be statistically significant. The validity of the data and information collected depends on the honesty of the respondent (Abawi, 2013). Questionnaires can be used to measure both quantitative and qualitative research data, but it is more suitable for a quantitative research data collection (Abawi, 2013).

6.6 The Measuring Instrument for this Study

A structured questionnaire is used as the measuring instrument for this study. The questions were designed based on a comprehensive literature study as relating to additive manufacturing education. They were developed based on factors/variables that were considered to foster effective additive manufacturing education at the university based on different literatures consulted and also, as stated in section 5.3 of Chapter 5, where sustainability of additive manufacturing education was discussed. The entire questionnaire is divided into dependent and independent variables. The questionnaire consists of well-detailed cover letter that explains the purpose of the research to the participant/respondents. The measuring instrument is divided into two sections (i.e. section A and Section B). The section A is contained the biographical information section of the respondents.

The section B contained the main body of the questionnaire. The first sub-section of the questionnaire contained questions that measure the respondents understanding and perception about ‘additive manufacturing technology’ and the impact of the technology to science and engineering based on their years of working with either high-end industrial additive manufacturing or an entry-level FDM 3D printing systems. The second sub-section, third sub-section, fourth sub-section and fifth sub-section consists of questions under AM technology transfer, AM educational curriculum, AM in-house facilities, and AM research and development respectively. The section B of the questionnaire also contains two open-ended questions. The five factors/variables considered in the questionnaire are described briefly below:

- **AM Technology:** This is the first sub-section in section B and each question is designed with an intent to examine the degree at which each respondent understands AM technology, and their perception and observation as relating to AM technology from an education point of view. Some of the questions in this sub-section also examine respondent views as relating to the impact AM technology on science and engineering education while working with either entry-level desktop 3D printers or the high-end industrial AM machines.

- **AM Technology Transfer:** The questions in this sub-section aimed at examining the respondent level of understanding and perception as relating to technology transfer by exploring the importance of university-industry collaboration and the benefit that 3D printing bureau can offer. The researcher identifies technology transfer as an important factor necessary for effective AM education framework.

- **AM Educational Curriculum:** AM is recognised as a technology that will play a major role in 21^{st} century STEM education globally. AM educational curriculum will serve as a platform to introduce AM education into the classrooms. The third sub-section of the questionnaire was designed to determine to what extent the respondents agree with the inclusion of AM education into SA universities science and engineering curriculum.

- **AM In-House Facilities:** Globally, in this era of industry 4.0, one of the ways to promote AM education and research activities at any university or research institute is the availability of AM/3D printing facilities at the faculty/department/school/colleges within the university (either the entry-level 3D printing machines or high-end industrial additive manufacturing machines). The facilities will serve as a great asset to the institution and it allows the academia and students to explore the potential in AM technology. This sub-section aimed to examine if the current AM facilities at the respondents' university are available for the use of students and for promoting AM education.

- **AM Research and Development (R&D):** Research and development assists organizations, industries and universities to obtain new knowledge and to create new technological innovation. To promote AM education at the university level; research and development is an important aspect to be considered. For effective research in AM, some factors are responsible for this, such as factors includes - funding, relevant standardization, patent registration, etc. The questions in fifth sub-section aimed to measure respondents' perspective as relating to research and development; and the role it would play in AM education framework.

6.6.1 Structure of the measuring instruments

The measuring instrument for this study is a structured questionnaire as earlier mentioned and the entire questionnaire was divided into two sections (A and B) as indicated in Figure 6.3.

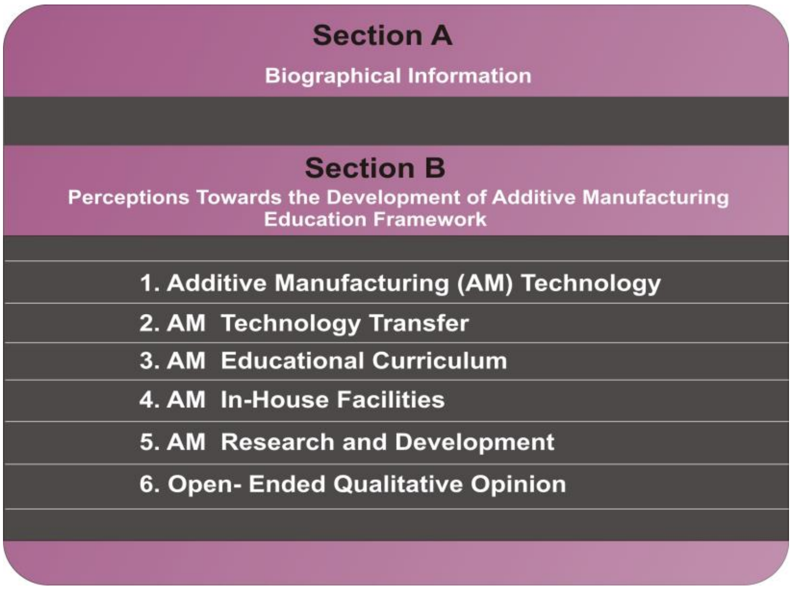


Figure 6. 2: The Questionnaire structure.

Source: Researcher's own construction

- **6.6.1.1 Section A: The biographical information**

Section A contains the biographical information as shown in Figure 6.4 and it contains five questions, although question 3 contains two sub-questions and question 4 contains four sub-questions. The respondents were requested to indicate their gender, age, current university or organization, year of study (undergraduate), type of postgraduate study (honours, masters, doctoral), field of study, position at the current university or organization (university's staff) and level of experience with AM education/technology. All the questions asked in section A of the questionnaire were considered very relevant to this study.

When the respondents indicated his/her age and gender in the questionnaire, this would assist the researcher in characterising the way each respondent perceived the need for an effective framework for additive manufacturing education at the university based on their gender and age bracket. When the respondent indicated his/her current university or organization, this would assist the researcher to classify each respondent based on their university. When the respondent ticked the appropriate year of study as an undergraduate student and type of study for a postgraduate student, this assists the researcher in characterising the respondent's stage or level of involvement with additive manufacturing technologies.

Also, when the respondent indicated his/her field of study, this would help the researcher in identifying some specific field of study where AM is currently being maximized or utilized. When respondent indicated his/her position at the current university or organization, this assists the researcher to understand the level of involvement and participation of the respondent in promoting and advancing AM education at the university. Lastly, when respondents indicated their level of experience with AM technology, this helps the researcher to categorize each respondent level of experience or understanding of the AM technology.

SECTION A - BIOGRAPHICAL INFORMATION

1. Gender: Male [1] Female [2]

2. Age: 15-20 years [ ] 21-25 years [ ] 26-30 years [ ] 31-35 years [ ] 36-40 years [ ] 41-45 years [ ] 46-50 years [ ]
Others [ ] years.

3. You are kindly advice to complete the one applicable to you

3a. Name of Your University: [ ]

3b. Name of Your Organization or company: [ ]

4. You are advise to only complete the one applicable to you in this section:

4a. For Undergraduate Student (Year of Study): circle appropriately [1] [2] [3] [4]

4b. For Postgraduate Student: circle appropriately Honours [1] Masters [2] Doctoral [3]

4c. Provide your field of study, write in the space from list below: [ ]

(1) Mechanical Engineering (2) Industrial Engineering (3) Electrical Engineering (4) Computer Engineering (5) Chemical Engineering (6) Information Technology (7) Information Engineering/Systems (8) Material Engineering (9) Science related degree (10) Others

4d. For University Staff: Tick/Write the appropriate one: AM researcher or expert [1]

Lecturer [2] Prof/ Associate Prof/ Senior lecturer/Lecturer/ Assistant Lecturer **Others** [3]

5. Level of Experience with AM education/technology: Basic [ ] Intermediate [ ] AM expert [ ] Novice [ ]

Figure 6. 3: Biographical Information for the questionnaire

Source: Researcher's own construction

- **6.6.1.2 Section B: The main body of the structured questionnaire**

Section B comprises of the main body of the research questionnaire as shown in Figure 6.3. The variables or the factors used in each sub-section of section B were identified through literature reviews as earlier mentioned and are considered useful and significant for the development of a framework for additive manufacturing education within the university context. Section B consists of five sub-sections and two open-ended questions. The first sub-section of the questionnaire contained fundamental questions which focuses on AM technology. The majority of the questions in section B of the questionnaire were divided into sub-questions such as (1.1a, 1.1b, 1.1c, till 1.1g.) and this was based on the advice of the statistical consultant assigned for the statistical analysis of this study at the NWU Statistical Consultation Service, the statistical consultant advised that lengthen question should be split into sub-questions to further enhance the result of the survey.

The other four sub-sections are key factors/variables to be considered in the development of AM education framework. The sixth sub-section contained two open-ended questions, and this allows the respondents to freely express themselves without any restriction of the scaled questions. Also, it gives the respondents opportunities to provide different insight. The main body of the measuring instrument contained a total number of 29 questions. A copy of the questionnaire can be found in Appendix A. Each of the sub-section in the questionnaire were clearly explained as follows:

<u>Section B - Sub-Section 1 of the Questionnaire</u> – Related questions on AM technology.

Figure 6.5 contained the fundamental questions on AM and the questions allows the respondents to express their own view/perception as relating to AM education at the university. The questionnaire used 5 points "Likert Scale" to measure the respondents' level of agreement with each question in the five sub-sections. The Likert scale used are (Strongly Agree, Agree, Neutral, Disagree and Strongly Disagree).

- **Questions 1.1a - 1.1g** were used to examine the respondents understanding of various *applications or usefulness of AM technology*. The questions also show if the respondents are very conversant with the trends within the AM sectors.

- **Questions 1.2a – 1.2f** were used to test respondents understanding of the *importance and advantages of AM technology*. The questions show the degree to which the respondents are familiar with various activities or application of AM technology in today's world.

- **Questions 1.3, 1.4, 1.8 and 1.9** were used examine *the present and future impacts of AM technology on science and engineering* education at the university. The questions show to what extent the respondents recognize the impact of AM technology and the sustainability of this technology.
- **Questions 1.5, 1.6 and 1.7** were used to examine the current *accessibility* to AM education and *acquisition of fundamental knowledge* of AM technology at SA universities. This questions also allow the respondents to give their perspective as whether AM technology is enhancing the science and engineering education at university.

SECTION B - PERCEPTIONS TOWARDS THE DEVELOPMENT OF ADDITIVE MANUFACTURING EDUCATION FRAMEWORK

	1. Additive Manufacturing (AM) technology - This section presents fundamental questions on additive manufacturing. Please indicate your level of agreement with the following statements by circling the appropriate options.	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
1.1	Additive manufacturing has been found to be useful in the following sectors:					
	a.) Manufacturing	1	2	3	4	5
	b.) Industrial design	1	2	3	4	5
	c.) Engineering	1	2	3	4	5
	d.) Dental and medical	1	2	3	4	5
	e.) Automotive	1	2	3	4	5
	f.) Aerospace	1	2	3	4	5
	g.) Education	1	2	3	4	5
1.2	Additive manufacturing technology has been found to:					
	a.) Reduces waste material,	1	2	3	4	5
	b.) Brings down labour costs	1	2	3	4	5
	c.) Speeds up the development	1	2	3	4	5
	d.) Speeds up the test phase	1	2	3	4	5
	e.) Allows for product customization	1	2	3	4	5
	f.) Ability to make complex metal parts	1	2	3	4	5
1.3	Additive manufacturing creates opportunity to improve new product development	1	2	3	4	5
1.4	AM education enhances the Science & Engineering degree at the university in South Africa	1	2	3	4	5
1.5	Most Science & Engineering students at SA universities have fundamental knowledge of AM	1	2	3	4	5
1.6	A number of Science & Engineering students at South African universities have access to AM technology for design purposes.	1	2	3	4	5
1.7	A number of Science & Engineering students at our university have access to AM technology for prototyping purposes	1	2	3	4	5
1.8	From Advance Manufacturing Perspective, AM is regarded as a Sustainable Technology	1	2	3	4	5
1.9	Establishment of "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Center" or 3D Printing Lab at other Universities in South Africa is having greater impact on Science & Engineering Education.	1	2	3	4	5

Figure 6. 4: Related questions on Additive Manufacturing (AM) technology

Source: Researcher's own construction

<u>Section B - Sub-Section 2</u> – Related questions on AM technology transfer

In Figure 6.6, the questions were used to investigate the extent to which the respondents understand the significant roles of "technology transfer" as relating to AM education and research activities. This section allows the respondents to indicate their level of agreement to questions relating to AM technology transfer.

	2 Technology Transfer – This section presents questions on technology transfer; the purpose of this section is to know respondent perspective as relating to "technology transfer". Please, indicate your level of agreement with the following statements by circling the appropriate options.	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.1	Technology transfer is the process of passing theoretical and practical skills, knowledge, manufacturing processes &technologies from the owner of a technology to a wider range of users.	1	2	3	4	5
2.2	Technology transfer ensures that:					
	a.) Scientific and technological development become more available in industry	1	2	3	4	5
	b.) Skills development of the university academic staff.	1	2	3	4	5
2.3	Technology transfer plays a major role:					
	a.) In the development of AM education at the university	1	2	3	4	5
	b.) In the integration of AM education at the university	1	2	3	4	5
2.4	University-industry collaboration on additive manufacturing processes will:					
	a.) Further enhance the university academic relations with industry	1	2	3	4	5
	b.) Further enhance the university students relations with industry	1	2	3	4	5
	c.) Promote more research at the university	1	2	3	4	5
	d.) Attract more scholarships/bursary to the universities	1	2	3	4	5
	e.) Attract more internships for the student at the university	1	2	3	4	5
2.5	3D printing bureau or organization could provide students, academic and industry engineers:					
	a.) with hands-on experience	1	2	3	4	5
	b.) with on-the-job experience.	1	2	3	4	5

Figure 6. 5: Related questions on Additive Manufacturing (AM) technology transfer

Source: Researcher's own construction

- **Questions 2.1, 2.2a – 2.2b and 2.3a – 2.3b** were used to examine respondent understanding of *the aim, roles and importance of "technology transfer"* in promoting AM education. The question shows the degree to which the respondents understand the significant and more so, the impact of technology transfer within a framework for AM education at the universities.
- **Questions 2.4a – 2.4e** were used to investigate the respondents' perspective of *the benefits of university-industry collaboration* in advancing AM education at the universities worldwide. The question in this sub-section shows the importance of technology transfer unit/department at any university, in creating a collaborative environment for university and industry to foster effective research activities (especially, in AM research).
- **Questions 2.5a – 2.5b** were designed to examine respondents' perceptions of *the involvement of 3D printing service bureau in supporting technology transfer* to students,

academics and industry professionals. The questions show the degree to which 3D printing bureau service/company can offer professional training to the university community and assist in setting up world-class 3D printing laboratory across campuses.

Section B - Sub-Section 3 – Related questions on AM Educational Curriculum

The questions in Figure 6.7 focuses on the educational curriculum in AM and the questions were used to investigate the need for inclusion of AM education/courses in the SA universities curriculum both undergraduate and postgraduate program; specifically, the Science, Technology, Engineering and Mathematics (STEM) degrees. AM technology cannot be properly integrated into the educational system at the universities without first being introduced as courses within the university curriculum, which will eventually increase the number of AM educator/ personnel/professionals in SA.

- **Question 3.1** was used to investigate the respondents' view to the *need for more AM personnel* in the field of additive manufacturing both within the universities and industries. This question shows the extent to which there is a shortage of skills and experts in the field of AM both in South Africa and globally.
- **Questions 3.2a – 3.2b, 3.3 and 3.4** were used to examine respondents' view as relating to *the inclusion of AM education/courses in science and engineering curriculum* at South African universities. The questions show to some extent at which there is a need for full-semester courses in AM to be introduce to the university curriculum and how it can assist majority of student to develop interest in this technology and later choose a career path in AM technology.
- **Question 3.6 and 3.7** was used to investigate the *suitability of entry-level 3D printers for AM education.* The questions show the degree to which the existing 3D printing lab at respondents' university is equipping students, academics and professionals with both basic and in-depth knowledge of the AM technology.

3. Educational curriculum - This section presents questions on AM education curriculum and the need for its inclusion in the educational system at the South Africa universities. Please indicate your level of agreement with the following statements by circling the appropriate options.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
3.1	More educated personnel in the field of additive manufacturing are needed in South Africa as the technology is rapidly growing at an exponential across industries.	1	2	3	4	5
3.2	Additive Manufacturing education could be included in the relevant:					
	a.) Undergraduate science and engineering courses at the universities	1	2	3	4	5
	b.) Postgraduate science and engineering courses at the universities	1	2	3	4	5
3.3	An introduction of AM technology courses as full-semester courses at the university would enhance and promote the educational aspect of the technology	1	2	3	4	5
3.4	An introduction of AM technology courses as full-semester courses would serve as mean to allow science and engineering students to develop interest in AM and creates career path in AM.	1	2	3	4	5
3.5	A suitable short-course program should be designed for engineers in industry which could provide them with:					
	a.) An exposure to AM machines (3D printers)	1	2	3	4	5
	b.) A hands-on-experiences of AM technology	1	2	3	4	5
	c.) An exposure to design and simulation techniques.	1	2	3	4	5
3.6	Entry level FDM desktop AM/3D printing machine is considered suitable for a Additive Manufacturing education at the University Level.	1	2	3	4	5
3.7	All the 3D printing Labs at South Africa Universities, specifically the "Idea 2 Product" Lab at VUT and NWU Pukke 3D Printing Center equipping students and professionals with both basic and in-depth knowledge of the AM technology	1	2	3	4	5

Figure 6. 6: Related questions on Additive Manufacturing (AM) Educational Curriculum

Source: Researcher's own construction

<u>Section B - Sub-Section 4</u> – Related questions on AM In-House Facilities

The questions in sub-section 4 as shown in Figure 6.7, directly address the availability of AM/3D printing facilities at the universities for students and academic staff. For researchers to achieve cutting edge research in AM, it is paramount for the institutions to have in-house AM facilities (either entry-level 3D printing machines or high-end industrial additive manufacturing systems). Also, the questions were used to examine to what degree the AM facilities at the universities are available for the use of students and academics and how far it is used to promote AM education, teaching, learning, and academic research.

- **Questions 4.1a – 4.1b and 4.2** were used to explore respondents' views as relating to *acquisition of in-house AM facilities and establishment of 3D printing Lab* at the universities as part of the effort of government to introduce effective AM education and research at the universities.

- **Questions 4.3a – 4.3d** were used to examine the respondent’s perceptions as to *how cutting-edge AM/3D printing facilities at the university* could support teaching, learning, academic research and industrial collaboration.

- **Questions 4.4a – 4.4d** were used to examine the respondents’ view as to what extent *the available or existing AM facilities* at the selected universities have assisted the students and academics in various ways such as prototype design, printing final products, teaching and research and final year projects.

4. AM In-house facilities – This section presents questions that relates to in-house AM/3D printing facilities at South African university to promote AM education and research activities. Please, indicate your level of agreement with the following statements by circling the appropriate options.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
4.1	Acquisition in-house AM/3D printing facilities at the university fosters:					
	a.) Effective additive manufacturing education	1	2	3	4	5
	b.) Effective additive manufacturing research	1	2	3	4	5
4.2	Establishment of AM/3D printing labs at the university would increase students interest in AM or 3D printing technology	1	2	3	4	5
4.3	A cutting edge in-house AM/3D printer facilities at our university supports:					
	a.) Teaching	1	2	3	4	5
	b.) Learning	1	2	3	4	5
	c.) Academic research	1	2	3	4	5
	d.) Industry collaboration	1	2	3	4	5
4.4	In-house AM facilities at selected universities in South Africa are available for students and aca					
	a.) For design and prototyping purposes	1	2	3	4	5
	b.) For final product printing purposes	1	2	3	4	5
	c.) For teaching and research activities (i.e. Masters and PhD student research)	1	2	3	4	5
	d.) For final or fourth year projects	1	2	3	4	5

Figure 6. 7: Related questions on Additive Manufacturing (AM) In-House Facilities

Source: Researcher’s own construction

<u>Section B - Sub-Section 5</u> – Related questions on AM Research and Development (R&D)

The questions in this sub-section centred on AM Research and Development’ abbreviated as (R&D). Research and Development are described as the process through which new knowledge and innovative technologies are be discovered and support improvement of existing knowledge and enhancement of new product development. R&D also foster multidisciplinary research and technological innovation which leads to scientific and industrial development. As shown in Figure 6.8, the questions in sub-section 5 are used to investigate key contributing factors that could promote effective R&D in AM education at the universities.

- **Question 5.1a – 5.1c, 5.2, 5.3 and 5.4,** were used to investigate some of the contributing factors towards effective research and development in AM. The questions in this sub-section are used to test respondents' understanding and perspective towards improving AM education and research activities in AM. Such contributing factors include - sufficient funding from appropriate governing bodies for research, AM standardization, AM patent registration, inclusion of a master's degree programme in AM and technological advancement in AM.

5. AM Research and development (R&D) – This section presents questions that relates to research and development of AM which should serve as a prominent driver for technological innovation. Please indicate your level of agreement with the following statements by circling the appropriate options..		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
5.1	In the advancement of AM; Research and development is playing a vital roles:					
	a.) In the creation of additive manufacturing standards (ISO/ASTM)	1	2	3	4	5
	b.) For registration of additive manufacturing patent	1	2	3	4	5
	c.) For innovative and technological advancement of AM	1	2	3	4	5
5.2	Inclusion of a MSc program in Additive Manufacturing at selected university in South Africa Would further strengthen AM Research and development at the universities/industries.	1	2	3	4	5
5.3	Annual fund and grant from the Department of Science and Technology (DST) would boost AM research output at various universities in South Africa.	1	2	3	4	5
5.4	Annual fund and grant from National Research Foundation (NRF) increases AM research output at various universities in South Africa.	1	2	3	4	5

Figure 6. 8: Related questions on Additive Manufacturing (AM) Research and Development (R&D)

Source: Researcher's own construction

<u>Section B - Sub-Section 6</u> – The Open-Ended Questions

This sub-section contained two open-ended questions as shown in Figure 6.9 the open-ended questions were expected to provide more insight into the five sub-section in section B of the questionnaire.

Open-Ended Questions

6a. Do you think inclusion of Additive Manufacturing education to science and engineering curriculum at South African universities is a good idea ?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

6b. Does the "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Center" or 3D Printing Lab at your University is having **positive impacts** on Additive Manufacturing education or **Promoting** AM education?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

Figure 6. 9: The Open-Ended Questions on Additive Manufacturing Education

Source: Researcher's own construction

6.7 Statistical analysis aspect of this Study

Statistical data analysis is a branch of science that deals with the collection, organization, analysis of data and drawing of inferences from the samples to the whole population (Ali and Bhaskar, 2016, Winter *et al.,* 2010). Statistical data analysis needs an acceptable design of the study, an appropriate selection of study sample and choice of applicable statistical test (Ali and Bhaskar, 2016). Statistical data analysis allows the researcher to make use of mathematical principles to determine how likely the sample result match the stated hypothesis as relating to a population (SSC, 2017). In this session, certain statistical methods that would be useful during data analysis and interpretation is considered, such as confidence interval, Cronbach's alpha coefficient, p-value, effect size, level of significance and others.

6.7.1 Confidence interval

Patino and Ferreira (2015) defined "a confidence interval (CI) as a measure of imprecision of the true effect size in the population of interest (for example, the difference between two means or relative risk) estimated in the study population". A confidence interval can be used to describe the major findings of a research study. The measure of impression is due to the sampling error caused by taking sub-samples of the population of interest and the estimate calculation in the study population is always the best estimate of the effect size in the source population (Patino and Ferreira, 2015). In the literature, the most common width of confidence intervals recorded is 95% confidence interval, but in situation where the researcher is interested in more or less confidence, 90% or 99% confidence interval can be considered.

According to Patino and Ferreira (2015) there is a unique relationship exist between the 95% CI and two-sided 5% level of significance, "for instance, in situation where the 95% confidence of interval for differences in effect does not include 0 for absolute measures of association (for example the mean differences) or 1 for relative measures of association (for example, odds ratios), it can be inferred that the association is statistically significant (Patino and Ferreira, 2015). There is a unique relationship between the 95% confidence interval and a two-sided 5% level of significance. When the 95% confidence interval for differences in effect does not include 0 for absolute measures of association (e.g., mean differences) or 1 for relative measures of association (e.g., odds ratios), it can be inferred that the association is statistically significant ($p < 0.05$), and a very good advantage of 95% confidence interval over the p-value is that CI provides information about the size of the effect and the uncertainty of the population estimate and the direction of the effect (Patino and Ferreira, 2015).

6.7.2 Statistical Significance

The term ‘statistical significance’ is most basically used in statistical hypothesis testing and the purpose is to determine the observed difference in a statistical significance test. Researcher needs to pay attention to the output of p-value and confidence interval around the effect size (Optimizely, 2017). **P-value** can be described as the probability value of observing an effect from a sample and a P-value of < 0.05 is referred to as the conventional threshold for accepting a statistical significance. While the **Confidence interval around effect size** described as the upper and lower bounds of what the whole experiment all about (Optimizely, 2017).

More so, a statistically significant result is not based on chance and it depends on sample size and effect size variables. Therefore, **Sample size** is describing the size or number of the participants or samples for a survey or an experiment. The larger your sample size the more confident is the result of the experiment. **Effect size** could be described as the size of the difference in results between the two sample sets and practical significance is indicated (Optimizely, 2017).

6.7.3 Cronbach’s alpha coefficient

Cronbach’s alpha (α) or coefficient alpha was developed by Lee Cronbach in 1951 (Cronbach, 1951). Cronbach’s Alpha provides a way to measure reliability and internal consistency of a test or scale. This is being expressed as a number between 0 and 1. The internal consistency explains the extent to which all the items in a test measure the same construct (Tavakol and Dennick, 2011). Cronbach's alpha is an index of reliability associated with the variation accounted for by the true score of the "underlying construct." Construct is the hypothetical variable that is being measured (Hatcher, 1994; Santos, 1999). Cronbach’s alpha can also be referred to as a function of number of test items and the average inter-correlation among items (IDRE, 2017). The standardized formula for Cronbach’s alpha is shown below:

$$\alpha = \frac{N \cdot \bar{c}}{\bar{v} + (N-1) \cdot \bar{c}}$$

Where: N = the number of items,

$\bar{c}$ = average covariance between item-pairs, and

$\bar{v}$ = average variance.

From different literature consulted, acceptable values for a Cronbach's alpha ranging from 0.07 to 0.95. (DeVellis, 2003; Nunnally and Bernstein, 1994; Bland and Altman, 1997). Tavakol and Dennick (2011) explains that a low value of alpha could be caused by low number of questions, poor interrelatedness between questions or constructs. Streiner (2003) describes that too high a Cronbach's alpha may suggest that some items are redundant because it shows they are testing the same questions but, in another manner, a maximum Cronbach's alpha value of 0.90 is recommended. While a high value of Cronbach's alpha (> 0.90) implies redundancies and it shows that the length of test must be shortened. Table 6.1 shows the description of Cronbach's alpha coefficient.

Table 6 1: A rule for interpreting Cronbach's alpha (Andale, 2017).

Cronbach's alpha	Internal consistency
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

6.7.4 Inter-item Correlations

According to (Piedmont, 2014) "Inter-item correlations are an essential element in conducting an item analysis of a set of test questions. Inter-item correlations examine the extent to which scores on one item are related to scores on all other items in a scale". Inter-item correlations give an assessment of item redundancy, that is, the degree at which questions on a scale are assessing the same content (Cohen & Swerdlik, 2005; Piedmont, 2014). Piedmont (2014) stresses that in a best possible way, the average inter-item correlation for a set of items should be between 0.20 and 0.40, and this shows that the items are reasonably homogenous which implies they have sufficient unique variance as to not be isomorphic with each other.

Piedmont (2014) stated that "when there is a value lower than 0.20, it shows that the items may not be representative of the same content domain and if the values are higher than 0.40, it indicates that the items may be only capturing a small bandwidth of the construct".

6.7.5 Descriptive Statistics for Skewness and Kurtosis of the data

Skewness and Kurtosis are commonly listed values in descriptive statistics function, and it is observed that the skewness and kurtosis give some insights into the shape of distribution.

Skewness is regarded as a measure of the symmetry in a distribution and it specifically measures the relative size of the two tails. For examples, when a symmetrical dataset has a skewness which is equal to 0, then, the normal distribution of the skewness is 0 (SPCForexcel, 2016). Kurtosis on the other hand, is the measure of the combined sizes of the two tails which measures the amount of the probability in the tails. The normal distribution for kurtosis is equal to 3, but if the kurtosis is > 3 the dataset is considered heavier than a normal distribution and if the < 3 the dataset is considered lighter tails than a normal distribution (SPCForexcel, 2016). The ***moment coefficient of skewness*** of a data set is skewness: $g_1 = m_3 / m_2^{3/2}$

$$\text{where } m_3 = \sum(x-\bar{x})^3 / n \quad \text{and} \quad m_2 = \sum(x-\bar{x})^2 / n$$

$\bar{x}$ is the mean and n is the sample size, as usual. m_3 is called the ***third moment*** of the data set. m_2 is the ***variance***, the square of the standard deviation while the ***moment coefficient of kurtosis*** of a data set is computed almost the same way as the coefficient of skewness: just change the exponent 3 to 4 in the formulas (Brown, 2017): kurtosis: $a_4 = m_4 / m_2^2$ and excess kurtosis: $g_2 = a_4 - 3$

$$\text{where } m_4 = \sum(x-\bar{x})^4 / n \quad \text{and} \quad m_2 = \sum(x-\bar{x})^2 / n$$

Again, the excess kurtosis is generally used because the excess kurtosis of a normal distribution is 0. $\bar{x}$ is the mean and n is the sample size, as usual. m_4 is called the ***fourth moment*** of the data set. m_2 is the ***variance***, the square of the standard deviation (Brown, 2017).

6.8 Chapter summary

This chapter has presented the term ‘empirical investigation’ and relevant scientific methods involved. The research methodology was discussed in detail and the measuring instrument as relating the research was presented. The chapter also discussed relevant statistical analysis methods needed for this research in chapter 7.

The next chapter presents the discussion and interpretation of statistical analysis. The hypothesis will be tested, and justification will be made about rejecting or accepting the hypotheses.

Chapter 7

7. Results, Analysis and Discussion

This chapter presents the results, analysis and discussion of the statistical analysis of the research. This chapter presents the statistical analysis of the biographical information in Section A of the questionnaire. The chapter also contained the interpretation of section B of the questionnaire which comprises of five sub-sections which contained five variables/factors [AM technology, AM technology transfer, AM educational curriculum, AM in-house facilities and AM research and development] and the chapter ends with a summary.

7.1 Descriptive Statistics

According to Thompson (2009) descriptive statistics refer to numbers that summarize the quantitative data with the aim of reporting what happened in the sample. Descriptive statistics are used to compare samples obtained from one or more study to assist researchers in identifying characteristics in samples that may influence the conclusions of a study. Descriptive statistics presents numerical data or facts in either tabular or graphical manner that can be easily analysed. Descriptive statistic is very significant in quantitative data analysis and can be used for two purposes. 1.) It provides fundamental information as relating to a dataset and 2.) It highlights possible relationships between variables. Leedy and Ormrod (2010) describe three descriptive statistics tools that is suitable for quantitative data analysis, which are: measure of central tendency, measure of variability and measure of association.

1. Measure of Central Tendency: This is the statistical measure that identifies one value as representative of a whole distribution (Gravetter and Wallnau, 2000; Manikandan, 2011). Measure of central tendency aims at providing a precise description of the whole data. The three most commonly used measures of tendency are **mean**, **median** and **mode**. Mean is the most commonly used measure of central tendency (Manikandan, 2011). It can be applied to both discrete and continuous data, although oftentimes it is used for continuous data. The median is the middle score for a set of data that has been arranged in order of magnitude. The mode is the most frequent score in our data set (Laerd-Statistics, 2018).

2. Measure of Variability: In statistics, it is also referred to as a measure of dispersion or spread. Measure of variability is a summary statistic which indicates the amount of dispersion in a dataset i.e. how the values spread out. It shows how far away the data points move to fall from the centre point. The most frequently used measure of variability by researchers are **range**,

interquartile range, **variance** and **standard deviation**. The range is the different between the lowest and highest values in a dataset, i.e. highest score minus the lowest score. The variance is the average squared difference of the values from the mean while standard deviation is the standard difference between each data point and the mean (Frost, 2018b).

3. Measure of Association: This is known as correlation that allows the researchers to determine the relationship between multiple variables (Maree, 2007; Van der Merwe, 2011). Measure of association are used statistic to measure the direction. The direction and strength of the correlation of two variables can be revealed by calculating the correlation coefficient (r). There are positive and negative directions. An ideal positive correlation coefficient = +1 while ideal negative correlation coefficient = -1. The correlation coefficient can be interpreted as stated below (Van der Merwe, 2011):

r = 0.1 indicates a small relationship between items;
r = 0.3 shows there is a medium relationship between items; and
r = 0.5 implies a strong relationship between items

7.2 Descriptive Statistics for the data analysis

The full descriptive statistics table for this study can be found in Appendix B. The descriptive statistics was captured based on 130 completed questionnaires received from 130 participants who took part in the survey. The descriptive statistics table contained only section B of the questionnaire and there are no "missing value" i.e. unusable questionnaire. The table provides the exact number of respondents that answer each question which shows the minimum samples (known as largest observation) and maximum samples (known as smallest observation), that is the values of the least and greater elements of the survey sample; based on the Liker scale used for the questionnaire (1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree and 5. Strongly Agree). The mean, M and standard deviation, SD is the measure of central tendency that was used, and the total number of the observation referred to the sum of N, i.e. I30 valid N (listwise) were recorded. During the discussion and interpretation of section B of the questionnaire, the descriptive statistics for each sub-section under section B will be presented in full detail.

7.3 Population and Sample Size for the study

According to Burmeister and Aitken (2012) "sample size is one element of research design that investigators need to consider as they plan their study. Although sample size is a consideration in qualitative research, the principles that guide the determination of sufficient sample size are different to those that are considered in quantitative research". Fox *et al.* (2009) further explain that sampling and sample size are important problems in pieces of quantitative study and this type of study seeks to make statistically based generalisations from the result of the study to a wider world. To adequately make a generalization in this manner, it is very necessary that the sample size and sampling method are suitable, such that the study results are representative and that the statistics can discern in association within the results of the research (Fox *et al.* 2009).

Burmeister and Aitken (2012) recommend that researchers can use sample size calculator to determine effective sample size and suggested that a sample of 100 should be sufficient for a quantitative research method. In most cases, sample sizes between 30 and 500 are generally accepted as sufficient for a quantitative study by many researchers (Delice, 2010). The senior statistical consultant at the NWU statistical consultation service that performed the statistical analysis for this study also recommends a sample size of 100 or 300 for this research. SPSS statistical software tool version 25 was used to analyse the data (SPSS Inc. 2017).

The target audience for the survey were mainly university students (both undergraduate and postgraduate) and academics, who have access to AM machines, or have used the AM/3D printing lab/facilities on their campuses for both academic and research purposes. Therefore, the sample size used in this study is 130 participants and the sample size for this survey is considered suitable for this type of research and would allow generalization of the findings. A total number of 200 questionnaires were handed out and 130 completed questionnaires were returned (a 65% response rate) while 70 questionnaires were not return (a 35% non-response rate) as shown in Figure 7.1.

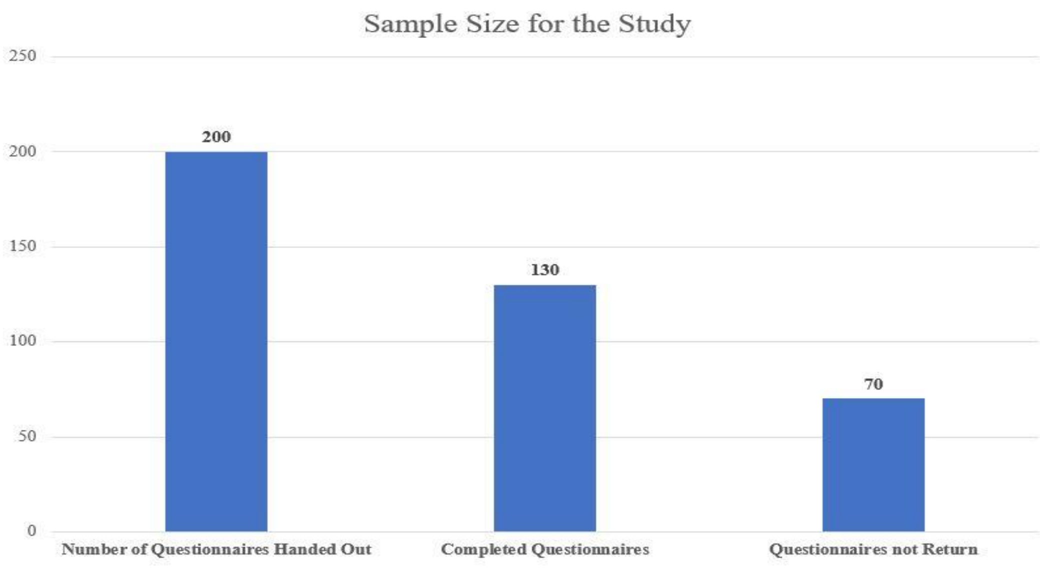


Figure 7. 1: The sample size for the study

Source: Researcher's own construction

7.4 Analysis of the respondents' biographical information

This section presents the biographical information of all the respondents as stated in section A of the questionnaire. The biographical section contained the respondent's gender, age range, name of the university/organization, level of study (undergraduate/postgraduate), field of study, present position (mainly for university staffs) and level of experience with AM technology as shown in Figure 6.4.

7.4.1 Gender of respondents

The gender of the respondents is presented in Figure 7.2 which indicates that 130 respondents consisted of 73 males (n = 56.2%) and 57 females (n = 43.8). Based on the percentage of male and female respondents in the survey, this shows that the percentage of males to females involvement in AM technology is relatively small (i.e. 16, n =12.3), and a sign that both males and females are embracing the AM technology within the education sector.

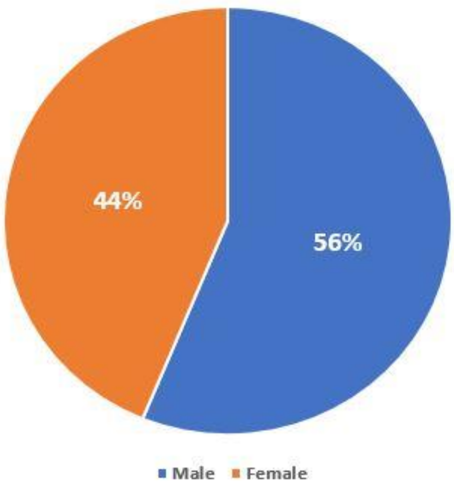


Figure 7. 2: Gender of the respondents
Source: Researcher's own construction

7.4.2 Age of the respondents

The majority of the respondents were within the age groups of 21 – 25 years (n = 70; 53.8%) and follows by 26 – 30 years (n = 40; 30.8%) as shown in Figure 7.3. Age groups within 31 – 35 years have 10 respondents (7.7%), while age groups 15 - 20, 36 – 40 and 41 – 45 have 5, 3 and 2 respondents respectively. There is no respondent who falls within age groups 46 - 50 years.

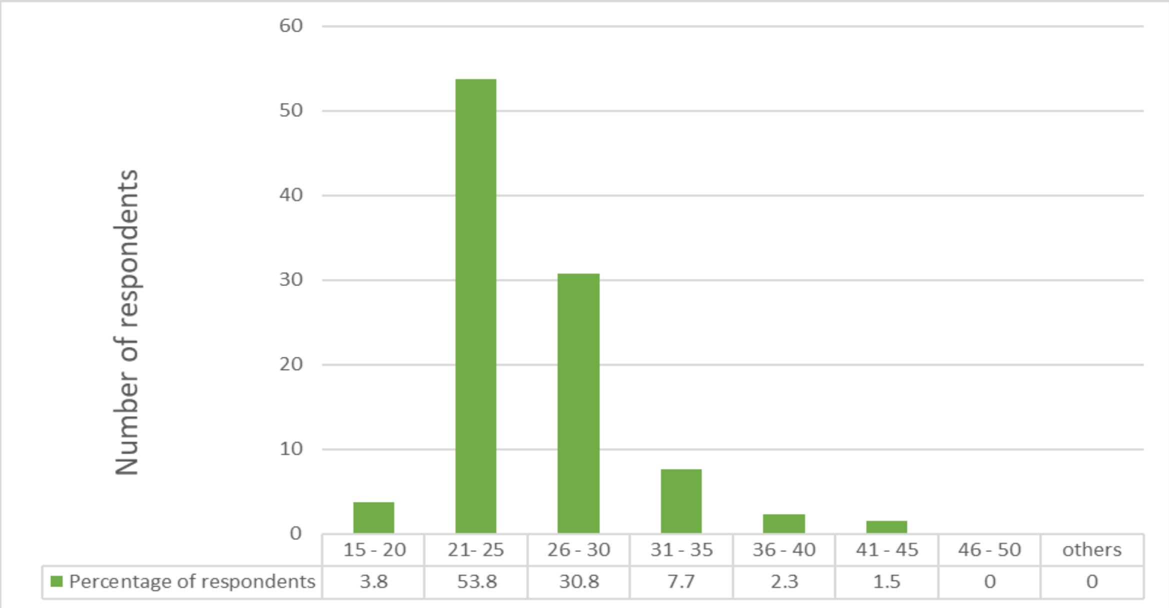


Figure 7. 3: Age of the respondents

Source: Researcher's own construction

7.4.3 Name of respondents' university/organization

From the section A of the questionnaire, there are two questions i.e. 3a and 3b, both questions are later considered as one question. Name of the respondents' university and organization assumed to be the same since the questionnaires were not distributed to industry/organization but only within the universities. At the beginning of the survey, two universities were primarily targeted which are Vaal University of Technology, VUT and North-West University, NWU because of the availability of 1dea 2 Product lab and 3D printing facilities at these universities. The researcher later considered two other universities (University of Johannesburg, UJ and University of the Witwatersrand, also known as Wits) to extend the survey coverage and to allow generalization of the findings.

VUT has the highest number of respondents participated in the survey, the survey covers the two campuses of VUT (Main and Sebokeng campuses), students, staffs and interns participated in the survey. Both the main campus and Sebokeng campus of VUT have Idea 2 Product laboratory and this is main reason why VUT has the highest number of participants (n = 64; 49.2%), follows by NWU with (n = 28; 21.5%) number of participants. NWU also have 3D printing lab/centre at the Potchefstroom campus. The number of participants from UJ and Wits are (n = 18; 13.8%) and (n = 20; 15.4%) respectively. Recently, UJ launches a 3D printing lab called "Makerspace Lab" with five 3D printers and a 3D scanner, while Wits University has a 3D printer within the School of Mechanical, Industrial and Aeronautical Engineering. Figure 7.4 shows the name of respondents' university/organization.

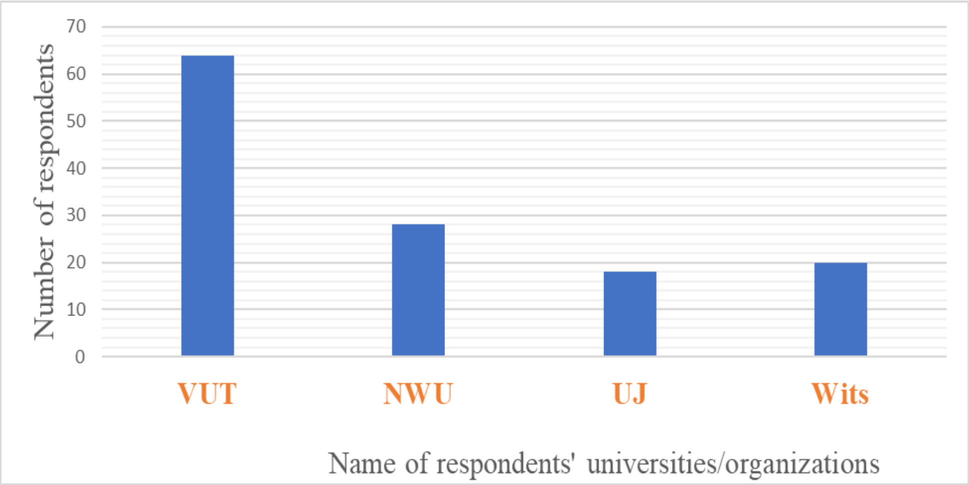


Figure 7. 4: Name of respondents' university/organization
Source: Researcher's own construction

7.4.4 Respondents' year of study – Undergraduate Students

This section of the biographical information requested that respondents within the undergraduate degree should indicate their year of study. The main reason for this section is to identify undergraduate student's level of involvement using AM technology based on their year of study. This shows that out of 130 participants in the survey, 59 of respondents are undergraduate students. 38 respondents indicate year 4, 14 respondents indicate year 3, 4 respondents are in year 2 and 3 respondent are in year 1 as shown in Figure 7.5. The highest number of respondents falls into year 4 of their study with 29.2%, follow by year 3 with 10.8%.

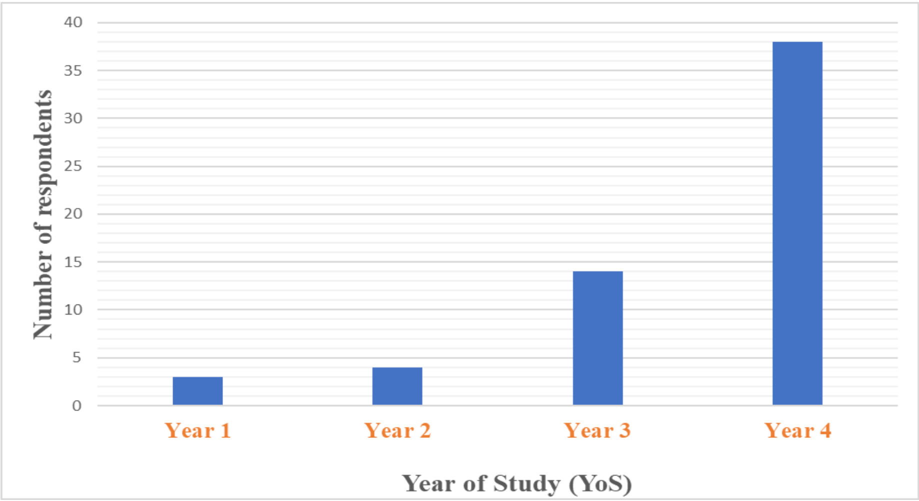


Figure 7. 5: Respondents' year of study (YoS) – Undergraduate students
Source: Researcher's own construction

7.4.5 Respondents' level of study – Postgraduate Students

The respondents were asked to indicate their level of study as postgraduate students. The researcher asked this question to classify postgraduate students based on their level of study (i.e. honours, master's and doctoral degree). This section of the questionnaire helps the researcher to know if postgraduate students have access to AM facilities and involved in AM researcher. Out of 130 respondents that completed the survey, 61 participants are postgraduate students. The master's degree students have the highest percentage of (n = 36; 27.7%), follows by doctoral students (n= 14; 10.8%) and honours students with (n = 11; 8.5%).

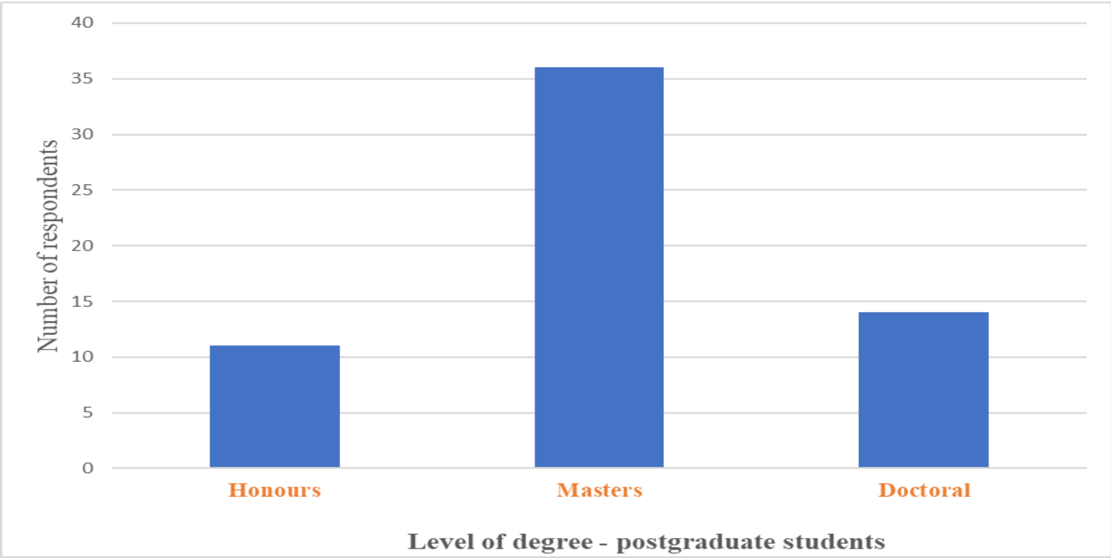


Figure 7. 6: Respondents' level of study – Postgraduate Students

Source: Researcher's own construction

7.4.6 Respondents' field of study

The respondents were asked to indicate their field of study to show which field of study within Science, Technology, Engineering and Mathematics (STEM) embracing additive manufacturing education and research. Out of 130 respondents that participated in the survey, 44 respondents indicate Mechanical Engineering with 33.8%, follows by Electrical Engineering with (n =18; 13.8%) and Industrial engineering with (n =17; 13.1%), while 8 respondents indicate chemical engineering (6.2%), 3 respondents are from computer engineering, 4 respondents indicate Information Technology with, 1 respondent each indicated Information Engineering/Systems and Material Engineering respectively.

The researcher could not list all the fields within the engineering degree and because of this, science related degree respondents and those outside science and engineering degree also indicated their field of study as shown in Figure 7.7. 11 respondents indicated science-related degrees (i.e. 8.5%); from this survey, the following were considered science related degree as indicated by the respondents [Metallurgical Engineering, Chemistry, Physics, Computer Science & Applied Sciences, Biomedical Engineering, Geology, Biochemistry, Process Instrumentation, Architectural Design, Aeronautical engineering]. 23 respondents indicate others (i.e. 17.7%) meaning courses that are not related to science and engineering degree, and as indicated by the respondents, others in this survey are [Human resource management, Operational Management, Legal science, Fine Arts, Business Management, Business Administration]. The result from this study shows that mechanical engineering field of study have the highest involvement with AM technology.

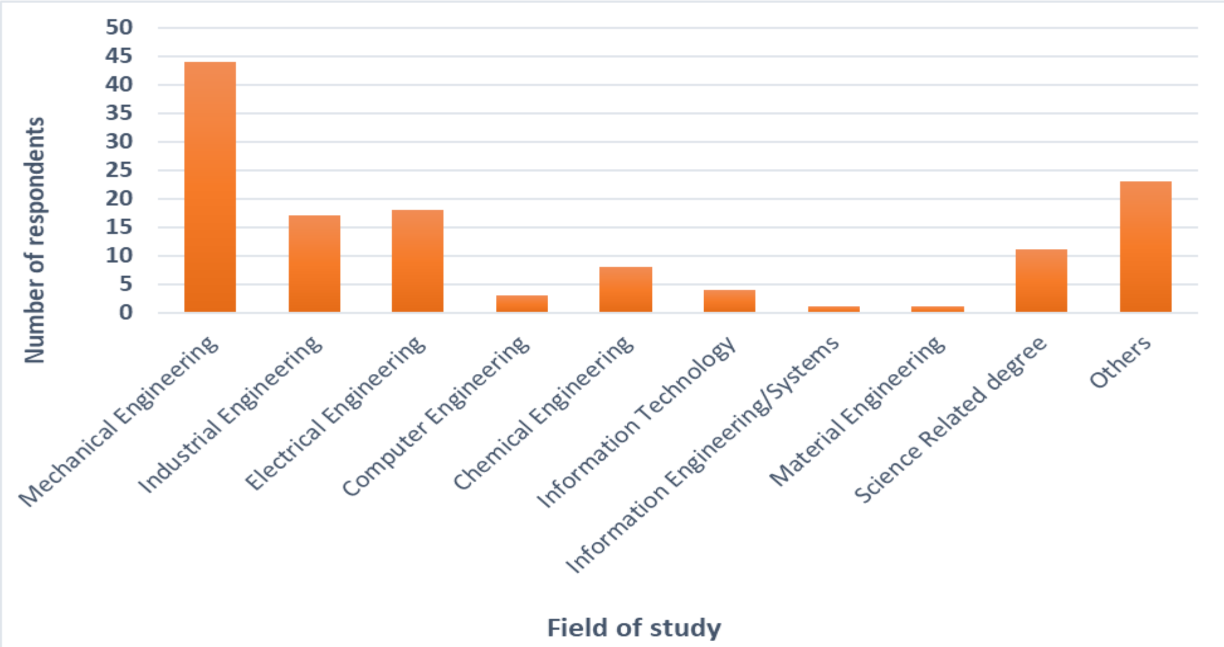


Figure 7. 7: Respondents' field of study
Source: Researcher's own construction

7.4.7 Respondent's position within the university/organization

The biographical information section also requested that respondents working within the university should indicate their position as academic staffs or AM researchers. This question allows the researcher to identify the number of academic staffs or AM researchers/experts that participated in the survey. Out of 130 respondents for the survey, 31 respondents are within this category. Others have the highest percentage of 12 respondents as shown in Figure 7.8, as indicated by the respondents, others are considered as [Lab Technician and Lab Assistant working with AM environment, Post-Doctoral fellows, Head-of Department at AM unit]. 11 respondents indicate AM researcher/expert and 8 respondents indicated lecturer, and those that indicated lecturer in this survey are (Junior and Senior lecturers). In this case, some respondents are currently either a master or doctoral student and still fall under the category of AM researcher/expert and lecturer. Likewise, some respondents are honours or masters' students and still working as a lab technician/lab assistant within the AM environment.

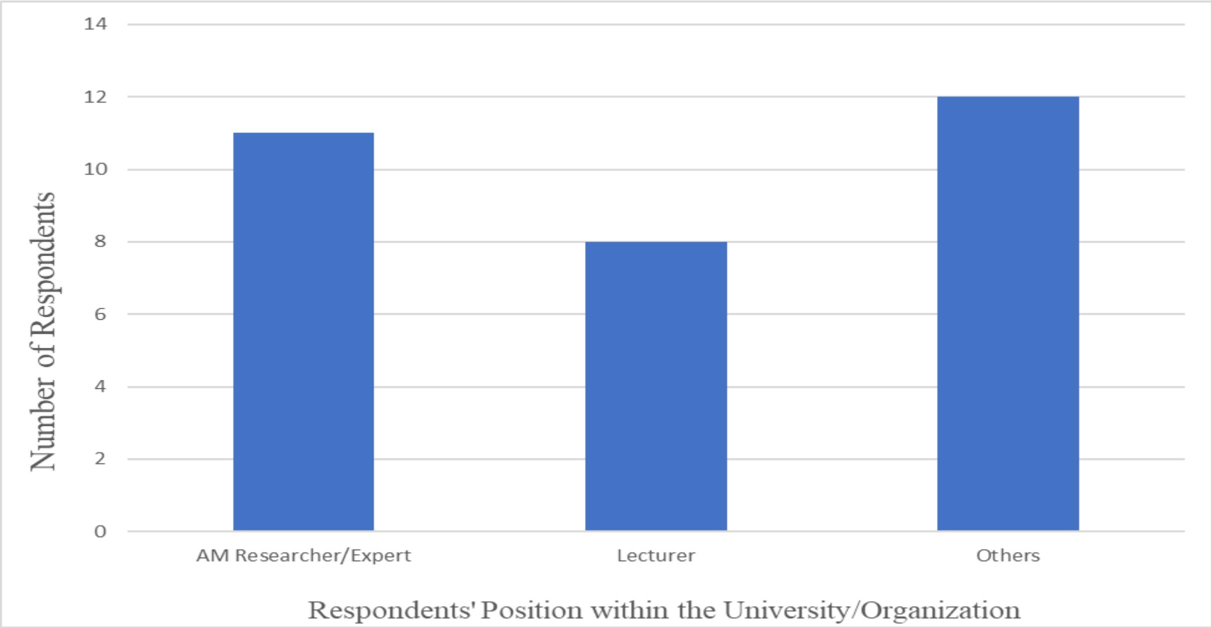


Figure 7. 8: Respondents' position within the university/organization

Source: Researcher's own construction

7.4.8 Respondents' level of experience with AM technology

Respondents were asked to give an indication of their level of experience working with AM technology. The respondents were able to achieve this by selecting from one of four levels of experience as shown in Figure 7.9. Majority of the respondents indicate "Basic knowledge of AM technology" with (n = 59; 45.4%), follows by "intermediate knowledge of AM technology" with 50 respondents with 38.5%, while 17 respondents indicate "AM expert" with 13.1% and only 4 respondents chosen "Novice to AM technology" with 3.1%. The percentage of respondents that selects either "basic and intermediate knowledge of AM" shows that majority of the respondents have worked with AM technology or have access AM facilities either the entry-level Desktop 3D printing machines or high-end industrial AM Machines. The respondents' response to this question indicate that most the respondents have good understanding of AM technology.

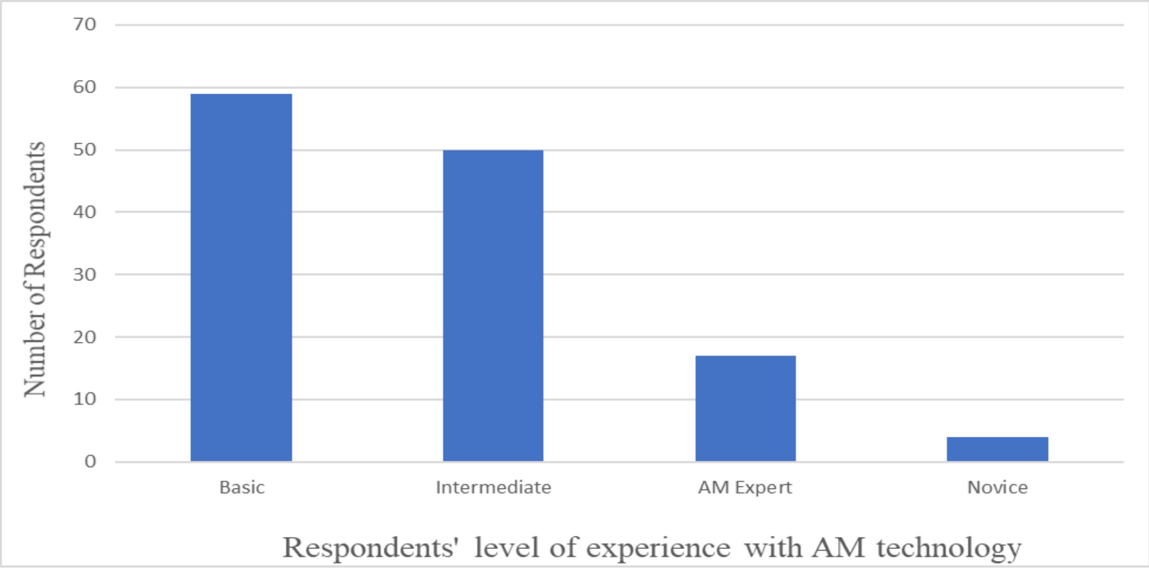


Figure 7. 9: Level of experience of respondents working with AM technology

Source: Researcher's own construction

7.5 Framework Responses – Statistical analysis of section B of the questionnaire

The section B of the questionnaire contained five sub-sections as stated in section 6.6 of Chapter 6. This framework comprises five factors/variables considered suitable for promoting effective AM education at the universities. These factors formed the basis for stated null (H_0) and alternative (H_1) hypotheses and this led to the development of the measuring instrument, i.e. the questionnaire which serve as a means for testing the hypotheses.

The main purpose of the questionnaire was to be used to examine respondents' perception towards additive manufacturing education and the technology itself. Section 7.5.1 to section 7.5.5 contained the descriptive statistical analysis of five factors in section B of the questionnaire. Section 7.7 examines the respondents' responses to the two open-ended questions in relation to the five factors in section B of the questionnaire. Appendix D shows the detailed feedback received from the respondents for the entire questionnaire in section B with the percentages of each question and total number of respondents that participated.

7.5.1 Sub-section 1 - AM Technology

The questions in this sub-section were directly related to the *fundamental of AM technology* and its *relation to education.* The questions also aimed to examine the impact of AM on science and engineering education. The sub-section contained 9 questions (i.e. 1.1 to 1.9). For statistical analysis purposes, the 9 questions were further sub-divided or grouped in four constructs. To achieve a proper grouping of the questions, pattern matrix was conducted as part of the factor analysis. According to Yong and Pearce (2013) "factor analysis is mathematically complex and is used to identify latent constructs or factors. The aim is to reduce variables into a smaller set to save time and facilitate easier interpretation. Statistician uses different extraction methods such as Maximum Likelihood and Principal Axis Factor". Bian (2017) explains that factors pattern matrix "contains the loadings that represent unique relationship of each items to a factor while controlling the correlations among factors". The pattern matrix was grouped into 3, 4 and 5 constructs, and only pattern matrix that allows four grouping make sense and was chosen as shown in Table 7.1.

Table 7. 1: Suitable Pattern Matrix[a] for grouping questions in sub-section 1 into 4 constructs

	Component			
	1	2	3	4
B1.1a	0.701			0.307
B1.1b	0.821			
B1.1c	0.874			
B1.1d	0.678			
B1.1e	0.658			
B1.1f	0.633		0.299	
B1.1g	0.629			
B1.2a		0.373	0.514	
B1.2b			0.724	
B1.2c			0.786	
B1.2d			0.692	
B1.2e			0.662	
B1.2f			0.469	
B1.3				0.679
B1.4				0.817
B1.5		0.804		
B1.6		0.907		
B1.7		0.878		
B1.8		0.506		0.320
B1.9		0.255		0.443

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 10 iterations.

- **7.5.1.1 Discussion and interpretation of sub-section 1 questions**

The respondents were requested to consider 9 questions and to choose the appropriate response as related to AM technology. This section contained the general descriptive statistic as shown in Table 7.2. The table shows the frequency percentage (%), the mean (M) and the standard deviation (SD) of the respondents. The rating scale: 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly agree. The questions in this sub-section are further divided into four constructs and each construct has its own internal reliability (i.e. Cronbach alpha) and average inter-item correlation.

Therefore, the first construct exhibited an average inter-item correlation of 0.463 and internal reliability of 0.853 Cronbach alpha; second construct indicated an average inter-item correlation of 0.351 and internal reliability of 0.762 Cronbach alpha; third construct showed an average inter-item correlation of 0.328 and internal reliability of 0.657 Cronbach alpha and the fourth construct indicated an average inter-item correlation of 0.696 and internal reliability of 0.872 Cronbach alpha which were based on the analysis of 130 valid responses. Cronbach alpha 0.853 and 0.872 is an acceptable reliability coefficient which suggests that the items contained a relatively high internal consistency, while Cronbach alpha 0.762 and 0.657 are also considered acceptable reliability coefficient (Nunnally and Bernstein, 1994; Reynaldo and Santos, 1999). The Kaiser-Meier-Olkin (KMO) for this sub-section is 0.788 which measure the sample adequacy and exceed the ‘acceptable good value’ of 0.70. To test if the correlations between items are higher enough, the Bartlett's test of sphericity is approx. chi-square 1102.310 and reached statistical significance of ($p < 0.000$), although if $p<0.05$, the correlations are considered sufficiently high (Pallant, 2011).

The questions in construct 1 centred on the *application or usefulness of AM technology* in various sectors such as manufacturing, engineering, dental and medical. The responses from majority of the respondents agreed that AM are very useful in various sectors, i.e. question 1.1a to 1.1g. 50.8% respondents indicated agreed and 4.46% indicated strongly agreed for Manufacturing sector’; 51.5% respondents selected agreed and 40.8% strongly agreed for ‘Industrial Design’; 47.7% indicated agreed and 46.9% strongly agreed with ‘Engineering sectors’; 39.2% selected agreed and 43.8% strongly agreed for ‘Dental and Medical sectors’; 43.8% indicated agreed and 41.5 strongly agreed for Automotive industry; 43.1% chosen agreed an 44,6% strongly agreed for Aerospace industry’; and 50.0% respondents indicated agreed and 41.5% strongly agreed for ‘Educator sector’. According to Posner (2018), “standard deviation is described as measure of the degree to which one’ observers agree or disagree with each other”. Therefore, in this construct, lower standard deviation occurred at 1.1a and 1.1c which implies that the people are in more agreement with one another, while the rest questions in this construct indicated higher standard deviation which implies that there is no relationship that linked with one another (Posner, 2018).

The questions in the second construct focused on *the importance and advantages of AM technology*. Most of the respondents that responded to these questions indicated ‘Agree’ compared to ‘Strongly agree’. This shows that the respondent recognized the advantages of AM technology across various sectors. 53.8% of the respondents indicated agreed and 26.9% strongly disagreed to the advantage of AM in ‘reducing waste material’; 62.3% selected agreed and 24.6% strongly agreed with the impact of AM in ‘bringing down labour cost’; 60.0%

respondents showed agree and 29.2% strongly agreed with advantage of AM in 'speeding up the development phase'; 53.8% of respondents indicated agree and 26.9 strongly agree to the use of AM 'speeding up the test phase'; 50.0% selected agreed and 39.2% strongly agreed that AM 'allows for use in product customization'; 45.4% agreed and 43.8% strongly agreed with the use of AM to 'make complex metal parts'. The standard deviation in this construct are higher and indicates that there is no relationship that linked with one another (Posner, 2018).

The third construct contained questions that centred on *the present and future impacts of AM technology on science and engineering education*. 48.5% of the respondents indicated agreed and 44.6% strongly agree to question 1.3, which implies that AM is creating more opportunities to improve new product development; 50.0% of the respondents selected agreed and 33.8% strongly agreed to question 1.4, which shows that majority of respondent agreed that AM education is enhancing the science and engineering degree at SA universities to a greater extent; 43.1% indicated agreed and 26.2% strongly agree, while 30.0% indicated neutral to question 1.8; this implies that majority of the respondents agreed that AM technology is a sustainable advance manufacturing technology; 43.1% chosen agreed and 42.3% strongly agreed to question 1.9 which indicates that the current 3D printing lab at selected universities in South Africa are equipping students and professionals with needed basic and advanced knowledge in AM technology.

The questions in the fourth constructs centred on the *accessibility and acquisition of fundamental knowledge of AM technology*. The respondents' feedback to questions in this construct has higher percentage of neutral, strongly disagree and disagree compared to responses received from previous three construct in sub-section 1. This could indicate that there is still low accessibility to AM technology and acquisition basic knowledge in AM among the science and engineering students. 34.6% indicated agreed and 24.6% strongly agreed, while 21.5% indicated neutral to question 1.5; 46.2% of respondents chosen agreed and 23.8% strongly agreed, while 13.8% selected neutral with 3.8% strongly disagreed to question 1.6; and finally, 40.0% respondents indicated agreed and 20.0% strongly disagreed, with 16.9% chosen disagreed to question 1.7. This construct has the highest standard deviation (1.102, 1.093 and 1.015) compared to the three previous construct and this occurred as result of the higher number of respondents that indicated 'neutral', 'strongly disagreed' and 'disagreed'.

Table 7. 2: AM education and technology related questions and respondents' responses (per construct)

AM Technology – Sub-section 1								
Likert Scale: 1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree; 5. Strongly Agree								
Construct 1: *Applications/ Usefulness of AM technology*		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M (%)	SD (%)
1.1 Additive manufacturing has been found to be useful in the following sectors:								
1.1a	Manufacturing	0	0	4.6	50.8	44.6	4.40	0.579
1.1b	Industrial Design	0	1.5	6.2	51.5	40.8	4.32	0.659
1.1c	Engineering	0	0	5.4	47.7	46.9	4.42	0.594
1.1d	Dental and Medical	1.5	1.5	13.8	39.2	43.8	4.22	0.856
1.1e	Automotive	0	2.3	12.3	43.8	41.5	4.25	0.758
1.1f	Aerospace	0	3.8	8.5	43.1	44.6	4.28	0.780
1.1g	Education	0	3.8	4.6	50.0	41.5	4.29	0.731
Construct 2: *importance and advantages of AM technology*								
1.2 Additive Manufacturing technology has been found to:								
1.2a	Reduces waste material	0	6.2	13.1	53.8	26.9	4.02	0.807
1.2b	Brings down labour cost	0	4.6	8.5	62.3	24.6	4.07	0.717
1.2c	Speeds up the development	0	0.8	10.0	60.0	29.2	4.18	0.628
1.2d	Speeds up the test phase	0	3.1	16.2	53.8	26.9	4.05	0.746
1.2e	Allows for product customization	0	0	10.8	50.0	39.2	4.28	0.650
1.2f	Ability to make complex metal parts	0	0.8	10.0	45.4	43.8	4.32	0.684
Construct 3: *The present and future impacts of AM technology on science and engineering education*								
1.3	Additive manufacturing creates opportunity to improve new product development.	0	0	6.9	48.5	44.6	4.38	0.613
1.4	AM education enhances the Science & Engineering degree at the university in South Africa.	0	6.2	10.0	50.0	33.8	4.12	0.822
1.8	From Advance Manufacturing Perspective, AM is regarded as a Sustainable Technology.	0.8	0	30.0	43.1	26.2	3.94	0.795
1.9	All the 3D printing Labs at South Africa Universities, specifically the "Idea 2 Product" Lab at VUT and NWU Pukke 3D Printing Centre equipping students and professionals with both basic and in-depth knowledge of the AM technology.	0	0	14.6	43.1	42.3	4.28	0.705
Construct 4: *Accessibility and acquisition of fundamental knowledge AM technology*								
1.5	Most Science & Engineering students at SA universities have fundamental knowledge of AM.	2.3	16.9	21.5	34.6	24.6	3.62	1.102
1.6	A number of Science & Engineering students at South African universities have access to AM technology for design purposes.	3.8	13.8	12.3	46.2	23.8	3.72	1.093
1.7	A number of Science & Engineering students at our university have access to AM technology for prototyping purposes.	0.8	16.9	22.3	40.0	20.0	3.62	1.015

RELIABILITY FOR AM TECHNOLOGY – SUB-SECTION 1			
Construct 1	Internal reliability: Cronbach alpha = 0.853	Average inter-item correlation = 0.463	N of Items = 7
Construct 2	Internal reliability: Cronbach alpha = 0.762	Average inter-item correlation = 0.351	N of Items = 6
Construct 3	Internal reliability: Cronbach alpha = 0.657	Average inter-item correlation = 0.328	N of Items = 4
Construct 4	Internal reliability: Cronbach alpha = 0.872	Average inter-item correlation = 0.696	N of Items = 3

Source: Researcher's own construction

- **7.5.1.2 Inter-item correlation matrix for sub-section 1 questions – AM Technology**

As stated in chapter 6 section 6.8.4, inter-item correlations matrices are described as vital elements when conducting an item analysis of a set of test questions and it also examine the extent at which the scores on each item are related to scores on all other items within a scale (Piedmont, 2014). When all the values in inter-item correlation matrix are positive, this indicates that all the items measured exactly the same underlying characteristics. Negative values in inter-item correlation shows that some of the items have not been correctly reversed-scored (Pallant, 2011:100). Often time, inter-item correlation tends to be relatively small in size ranging from 0.15 to 0.20, except in some cases where the items are simple restatements of another (Miller *et al.* 2012)

In this study, the inter-items correlation matrix was conducted based on each construct. Therefore, sub-section 1 contained 4 inter-items correlation matrix as seen Appendix E. Correlations are expected to be statistically significant at the level of 5% (i.e. p>0.005). The inter-item correlation matrix for construct 1, 2, 3 and 4 have no negative value present and this implies that all the items measured the same underlying characteristics. This indicates that the inter-item correlation matrix for construct 1, 2, 3 and 4 are statistically significant at level 0.50, 0.40, 0.30 and 0.60 respectively.

Table 7.3 below shows the component correlation matrix of the four constructs for questions in sub-section 1. To identify correlation between factors, three guideline values are considered very important: ***~0.1, small, no practical significant relationship, ~0.3, medium, practical visible relationship, and ~0.5, large, practical significant relationship.***

Therefore, the relationship between the first and seconds construct considered to be small relationship with correlation coefficient of 0.124, which implies that there is no practical significant relationship or link between first and second construct. Also, there is a small relationship between third and fourth constructs with correlation coefficient of 0.206.

Table 7. 3 Component Correlation Matrix per construct for sub-section 1 questions

Component	1	2	3	4
1	1.000	0.124	0.293	0.067
2	0.124	1.000	0.265	0.119
3	0.293	0.265	1.000	0.206
4	0.067	0.119	0.206	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

7.5.2 Sub-section 2 - AM Technology Transfer

The questions in sub-section 2 were directly related to *technology transfer* from an AM perspective. The sub-section aimed to examine the importance of technology transfer in promoting AM technology within the education sector. This sub-section contained five questions (i.e. 2.1 to 2.5). Some questions were divided into sub-questions. The five questions were further grouped into 3 constructs. A pattern matrix was conducted to investigation or identify the groupings that make sense. The pattern matrix was initially grouped into 2 and 3 constructs respectively and the pattern matrix with 3 construct grouping make sense as seen in Table 7.4.

Table 7. 4: Suitable Pattern Matrix[a] for grouping questions in sub-section 2 into 3 constructs

	Component		
	1	2	3
B2.1	0.731		
B2.2a	0.835		
B2.2b	0.862		
B2.3a	0.819		
B2.3b	0.826		
B2.4a		0.877	
B2.4b		0.834	
B2.4c		0.780	
B2.4d		0.532	0.391
B2.4e		0.314	0.658
B2.5a			0.574
B2.5b			0.908

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a Rotation converged in 8 iterations

- **7.5.2.1 Discussion and interpretation of sub-section 2 questions**

The respondents were asked to consider 5 questions within the 3 constructs and to indicate the appropriate response as related to AM technology transfer. This section contained the general descriptive statistic as shown in Table 7.5. The first, second and third construct exhibited an internal reliability of 0.883, 0.840 and 0.615 Cronbach alpha respectively based on the analysis of 130 valid responses. The three Cronbach alpha are considered acceptable reliability coefficients (Nunnally and Bernstein, 1994). The Kaiser-Meier-Olkin (KMO) for this sub-section is 0.746 which measures the sample adequacy and exceeds the ‘acceptable good value’ of 0.70. To test if the correlations between items are high enough, the Bartlett's test of sphericity is approx. chi-square 915.226 and reached statistical significance of ($p < 0.000$). The frequency percentage mean (M) and standard deviation (SD) of the responses from the respondents as relating questions on AM technology transfer are next presented.

The questions in the first construct directly centred on the *aim, roles and importance of technology transfer* within the context of AM. 39.2% of the respondents indicated agreed and

52.3% selected strongly agreed to question 2.1. This implies that the majority of the respondents have a good understanding of the term ‘technology transfer’. In question 2.2a, 45.4% indicated agreed and 44.6% strongly agreed. 45.4% chosen agreed and 42.3% strongly agreed to question 2.2b. This shows that most of the respondents agreed that technology transfer provides skills development for university staffs and makes both scientific and technological development available in the industry. Question 2.3a received 44.6% agreed, 39.2% strongly agreed and 15.4% neutral while question 2.3b received 44.6% agreed, 40.8% strongly agreed, and 13.8% neutral. This implies the respondents believe that technology transfer is playing a significant role in development and integration of AM education at the university. However, questions 2.3a and 2.3b have high degrees of neutral responses which implies that some respondents do not recognize the importance of technology transfer to AM education.

The second construct centred on the *benefits of the university-industry collaboration in AM technology transfer.* Question 2.4a to 2.4e shows that majority of the respondents understand the importance or the benefits of university-industry collaboration in advancing AM education and promoting cutting edge research. Question 2.4a recorded 57.7% agreed and 36.2% strongly agreed; question 2.4b have 60.8% agreed and 33.8% strongly agreed; question 2.4c received 54.6% agreed and 36.2% strongly disagreed; question 2.4d recorded 43.8% agreed, 33.8% strongly agreed and 17.7% neutral; and lastly, question 2.4e have 41.5% agreed, 33.8% strongly agreed and 18.8% neutral. The high neutral responses from questions 2.4d and 2.4e which shows that some respondents do not fully agreed that university-industry collaboration could attract more scholarship and internship for the students at the university.

The third construct focused on the *involvement of 3D printing service bureau in AM technology transfer*. The majority of the respondents agreed that the involvement of 3D printing bureau service could provide both hand-on and on-the-job experience of AM to students, academic and industry professional if there is a strong relationship between the university and the 3D printing service bureau in the country. 53.1% of the respondents indicated agree and 37.7% strongly agreed to question 2.5a. For question 2.5b, 43.1% of the respondents selected agreed and 33.8% strongly agreed, although same question 2.5b received 13.8% neutral responses which indicates that few respondents do not agree that 3D printing bureau service can provide on-the-job experience as a means for technology transfer.

In sub-section 2 questions, the highest standard deviation (SD) occurred in questions 2.3b, 2.4d, 2.4e, and 2.5b with SD of 0.748, 0.837, 0.880, and 0.944 respectively. This was due to high numbers of neutral responses received for these questions.

Table 7. 5: AM Technology Transfer related questions and respondents' responses (per construct)

AM TECHNOLOGY TRANSFER – SUB-SECTION 2								
Likert Scale: 1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree; 5. Strongly Agree								
Construct 1: *Aim, roles and importance of Technology Transfer*		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M (%)	SD (%)
2.1	Technology transfer is the process of passing theoretical and practical skills, knowledge, manufacturing processes &technologies from the owner of a technology to a wider range of users.	0.8	0	7.7	39.2	52.3	4.42	0.703
2.2	Technology transfer ensures that:							
2.2a	Scientific and technological development become more available in industry	0	0.8	9.2	45.4	44.6	4.34	0.677
2.2b	Skills development of the university academic staff.	0	0.8	11.5	45.4	42.3	4.29	0.698
2.3	Technology transfer plays a major role:							
2.3a	In the development of AM education at the university	0	0.8	15.4	44.6	39.2	4.22	0.729
2.3b	In the integration of AM education at the university	0.8	0	13.8	44.6	40.8	4.25	0.748
Construct 2: *Benefits of University-Industry collaboration in AM Technology Transfer*								
2.4 University-industry collaboration on additive manufacturing processes will:								
2.4a	Further enhance the university academic relations with industry	0	0.8	5.4	57.7	36.2	4.29	0.603
2.4b	Further enhance the university students' relations with industry	0	0	5.4	60.8	33.8	4.28	0.560
2.4c	Promote more research at the university	0	0.8	8.5	54.6	36.2	4.26	0.642
2.4d	Attract more scholarships/bursary to the universities	0	4.6	17.7	43.8	33.8	4.07	0.837
2.4e	Attract more internships for the student at the university	0	6.2	18.5	41.5	33.8	4.03	0.880
Construct 3: *Involvement of 3D printing service bureau/company in AM Technology Transfer*								
2.5	3D printing bureau or organization could provide students, academic and industry engineers:							
2.5a	With hands-on experience	0	0	9.2	53.1	37.7	4.28	0.625
2.5b	With on-the-job experience.	0.8	8.5	13.8	43.1	33.8	4.01	0.944

RELIABILITY FOR AM TECHNOLOGY TRANSFER – SUB-SECTION 2			
Construct 1	Internal reliability: Cronbach alpha = 0.883	Average inter-item correlation = 0.603	N of Items = 5
Construct 2	Internal reliability: Cronbach alpha = 0.840	Average inter-item correlation = 0.530	N of Items = 5
Construct 3	Internal reliability: Cronbach alpha = 0.615	Average inter-item correlation = 0.482	N of Items = 2

Source: Researcher's own construction

- **7.5.2.2 Inter-item correlation matrix for sub-section 2 questions – AM Technology Transfer**

The inter-items correlation matrix for this sub-section is divided into three constructs as shown in Appendix E. Correlations are expected to be statistically significant at the level of 5% (i.e. p>0.005). The inter-item correlation matrix for constructs 1, 2 and 3 have no negative values present and this implies that the inter-item correlation matrix for construct 1, 2 and 3 is statistically significant at the level 0.50, 0.60 and 0.40 respectively (Piedmont, 2014). Table 7.6 shows the component correlation matrix of the three constructs of the questions in sub-section 2.

Table 7.6 below shows the component correlation matrix of the three constructs for questions in sub-section 2. The key guidelines to identify correlation between factors are: ***~0.1, small, no practical significant relationship, ~0.3, medium, practical visible relationship, and ~0.5, large, practical significant relationship.*** Therefore, the relationship between the 'first and second' constructs, and 'second and third' constructs considered to be medium relationship with correlation coefficient of 0.357 and 0.384 respectively and this implies that there is practical visible relationship.

Table 7. 6: Component correlation matrix per construct in sub-section 2

Component	1	2	3
1	1.000	0.357	0.293
2	0.357	1.000	0.384
3	0.293	0.384	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

7.5.3 Sub-section 3 – AM Educational Curriculum

This sub-section contained 7 questions (i.e. 3.1 to 3.7) and the questions centred on the importance of education curriculum in AM technology. The questions were further grouped into 3 construct using pattern matrix as conducted by the statistical consultant that handled the statistical analysis of this study. The pattern matrix was initially grouped in 2 and 3 constructs, and the pattern matrix with 3 construct grouping make sense as shown in Table 7.7.

Table 7. 7: Suitable Pattern Matrix[a] for grouping questions in sub-section 3 into 3 constructs

	Component		
	1	2	3
B3.1		0.498	
B3.2a		0.850	
B3.2b		0.839	
B3.3		0.793	
B3.4	0.291	0.617	
B3.5a	0.830		
B3.5b	0.945		
B3.5c	0.828		
B3.6			0.745
B3.7			0.827

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

a. Rotation converged in 8 iterations.

- **7.5.3.1 Discussion and interpretation of sub-section 3 questions**

This section contained the general descriptive statistic for sub-section 3 questions with each question frequency percentage, mean (M) and standard deviation (SD) as shown in Table 7.8. The first, second and third construct exhibited an internal reliability of 0.827, 0.870 and 0.695

Cronbach alpha respectively based on the analysis of 130 valid responses. The three Cronbach alpha are considered acceptable reliability coefficients (Nunnally and Bernstein, 1994). The Kaiser-Meier-Olkin (KMO) for this sub-section is 0.761 which measures the sample adequacy and exceeds the 'acceptable good value' of 0.70. To test if the correlations between items are high enough, the Bartlett's test of sphericity is approx. chi-square 595.237 and reached statistical significance of ($p < 0.000$).

The questions in the first construct centred on *the need for more AM personnel or experts to promote AM education and research*. The feedback shows that majority of respondents agreed that more personnel and experts are needed in the field of AM and ways to achieve this would come through the introduction of AM education curriculum at the universities. 43.1% of the respondents indicated agreed and 53.1% chosen strongly agreed to question 3.1; 48.5% indicated agreed and 43.8% strongly agreed to question 3.2a; 54.6% selected agreed and 39.2% strongly agreed to question 3.2b which show that the respondents are interested in the introduction of AM education curriculum to both undergraduate and postgraduate program in science and engineering. Question 3.3 received 55.4% agreed responses and 36.2% strongly agreed, while question 3.4 recorded 53.1% agreed and 39.2% strongly agreed responses which indicates respondents' strong interest in introducing of a full semester courses in AM education.

The questions in the second construct focused *on the inclusion of AM education/courses in science and engineering education at the universities*. Most of the respondents agreed that suitable short-course programmes should be designed for engineers or professional in the industry to expose them to AM technology. Question 3.5a received 51.5% agreed and 44.6% strongly agreed; question 3.5b recorded 53.1% agreed and 41.5% strongly agreed, and question 3.5c has 49.2% agreed and 40.0% strongly agreed.

The questions in the third construct centred on *the suitability of entry-level 3D printers for AM education at the universities*. Most of the respondents agreed that entry-level 3D printers are most suitable for AM education at the university level and the reason for this can be linked to the fact that entry-level 3D printing machines are very affordable and easy to set up compared to high-end industrial AM machines which is very expensive and unaffordable for most universities to launch at their universities. Therefore, question 3.6 received 53.1% agreed and 39.2% strongly agreed, while question 3.7 recorded 46.2% agreed, 40.8% strongly agreed and 10.8% neutral responses.

Table 7. 8: AM Educational Curriculum related questions and respondents' responses (per construct)

AM EDUCATIONAL CURRICULUM – SUB-SECTION 3								
Likert Scale: 1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree; 5. Strongly Agree								
Construct 1: ***Need for more AM personnel in the field of AM***		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M (%)	SD (%)
3.1	More educated personnel in the field of additive manufacturing are needed in South Africa as the technology is rapidly growing at an exponential across industries.	0	0	3.8	43.1	53.1	4.49	0.574
3.2	Additive Manufacturing education could be included in the relevant:							
3.2a	Undergraduate science and engineering courses at the universities.	0	0	7.7	48.5	43.8	4.36	0.623
3.2b	Postgraduate science and engineering courses at the universities.	0	0.8	5.4	54.6	39.2	4.32	0.613
3.3	An introduction of AM technology courses as full-semester courses at the university would enhance and promote the educational aspect of the technology.	0	0	8.5	55.4	36.2	4.28	0.610
3.4	An introduction of AM technology courses as full-semester courses would serve as mean to allow science and engineering students to develop interest in AM and creates career path in AM.	0	0	7.7	53.1	39.2	4.32	0.610
Construct 2: ***Inclusion of AM education/courses in science and engineering curriculum***								
3.5 A suitable short-course program should be designed for engineers in industry which could provide them with:								
3.5a	An exposure to AM machines (3D printers).	0	0.8	3.1	51.5	44.6	4.40	0.592
3.5b	A hands-on-experiences of AM technology.	0	0	5.4	53.1	41.5	4.36	0.584
3.5c	An exposure to design and simulation techniques.	0.8	0	10.0	49.2	40.0	4.28	0.705
Construct 3: ***Suitability of entry-level 3D printers for AM education***								
3.6	Entry level FDM desktop AM/3D printing machine is considered suitable for Additive Manufacturing education at the University Level.	0	0	7.7	53.1	39.2	4.32	0.610
3.7	All the 3D printing Labs at South Africa Universities, specifically the "Idea 2 Product" Lab at VUT and NWU Pukke 3D Printing Centre equipping students and professionals with both basic and in-depth knowledge of the AM technology	0	2.3	10.8	46.2	40.8	4.25	0.740

RELIABILITY FOR AM EDUCATIONAL CURRICULUM – SUB-SECTION 3			
Construct 1	Internal reliability: Cronbach alpha = 0.827	Average inter-item correlation = 0.544	N of Items = 4
Construct 2	Internal reliability: Cronbach alpha = 0.870	Average inter-item correlation = 0.704	N of Items = 3
Construct 3	Internal reliability: Cronbach alpha = 0.695	Average inter-item correlation = 0.542	N of Items = 2

Source: Researcher's own construction

- **7.5.3.2 Inter-item correlation matrix for sub-section 3 questions – AM Educational Curriculum**

The inter-items correlation matrix for sub-section 3 is divided into three constructs as shown in Appendix E. The correlation coefficients are expected to be statistically significant at the level of 5% (i.e. p>0.005). The inter-item correlation matrix for construct 1, 2 and 3 are statistically significant at the level 0.5, 0.6 and 0.7 respectively (Piedmont, 2014). The inter-items correlation matrix for sub-section 3 has no negative values and this indicates that all the items measured the same underlying characteristics (Pallant, 2011). Table 7.9 presents the component correlation matrix for the three constructs in sub-section 3 based on three rules for identifying correlation between factors, i.e. *~0.1, small, no practical significant relationship, ~0.3, medium, practical visible relationship, and ~0.5, large, practical significant relationship.* Therefore, the relationship between the first and second constructs is regarded as a "medium" with correlation coefficient of 0.351 i.e. there is practically visible relationship. The relationship between second and third constructs is considered “small” with correlation coefficient of 0.098 which implies no practical significant relationship.

Table 7. 9: Component correlation matrix for sub-section 3 questions

Component	1	2	3
1	1.000	0.351	0.269
2	0.351	1.000	0.098
3	0.269	0.098	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

7.5.4 Sub-section 4 – AM In-House Facilities

In sub-section 4 of the questionnaire, the questions were directly related to AM in-house facilities, i.e. the available of AM/3D printing machines at the university to enhance and promote AM education and research. This sub-section contained 4 questions (i.e. 4.1 to 4.4). Majority of the questions in this sub-section were further divided into sub-question to facilitate the statistical analysis and interpretation. The factor pattern matrix analysis was conducted on the question to identify the grouping that makes sense. The pattern matrix was initially grouped into 2 and 3 constructs, and the pattern matrix grouping of 3 constructs were chosen as shown in Table 7.10.

Table 7. 10: Suitable pattern Matrix[a] for grouping questions in sub-section 4 into 3 constructs

	Component		
	1	2	3
B4.1a			0.895
B4.1b			0.902
B4.2			0.803
B4.3a	0.604		0.291
B4.3b	0.839		
B4.3c	0.829		
B4.3d	0.846		
B4.4a		0.814	
B4.4b		0.830	
B4.4c		0.871	
B4.4d		0.750	

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a Rotation converged in 7 iterations

- **7.5.4.1 Discussion and interpretation of sub-section 4 questions**

This sub-section contained the general descriptive statistics with the frequency percentages, mean (M) and the standard deviation (SD) as shown in Table 7.11. The first, second and third construct exhibited an internal reliability of 0.850, 0.822 and 0.839 Cronbach alpha respectively based on the analysis of 130 valid responses and the three Cronbach alpha are considered acceptable reliability coefficients (Nunnally and Bernstein, 1994). The Kaiser-Meier-Olkin (KMO) for this sub-section is 0.785 which measures the sample adequacy and exceeds the 'acceptable good value' of 0.70. To test if the correlations between items are higher enough, the Bartlett's test of sphericity is approx. chi-square 671.181 and reached statistical significance of ($p < 0.000$).

In sub-section 4, the questions in the first construct centred on *the acquisition of in-house AM/3D printing facilities and the establishment of 3D printing lab*. The questions aimed to examine the respondents' view as relating to the acquisition of AM facilities at the university and the need to set-up 3D printing lab such as (Idea 2 Product lab) at the university to promote effective AM education and research. The majority of the respondents show their level of agreement to the questions in this construct. Question 4.1a received 51.5% of agreed and 42.3% of strongly agreed; 54.6% of the respondents indicated 54.6% agreed and 39.2% strongly agreed to question 4.1b. Question 4.2 received 55.4% of agreed and 40.05 of strongly agreed.

The questions in the second construct focused on *the cutting-edge AM facilities at the university as a tool to support teaching, learning, academic research and industry collaboration*. The questions examine to which extent is the availability of AM facilities at the universities serve as a tool to promote AM education. The feedback shows that most of the respondents agreed with the questions. 58.5% of the respondents agreed and 32.3% strongly agreed to question 4.3a; 60.0% chosen agreed and 30.8% strongly agreed to question 4.3b; also, question 4.3d received 56.9% agreed and 38.5% strongly agreed as shown in Table 7.11.

The third construct centred on *the effectiveness of the available/existing AM facilities at the university*. The questions aimed to examine respondents' views as relating to the accessibility of the existing AM facilities at the university for students and academics use. Question 4.4a received 50.8% of agreed and 36.9% strongly agreed; 48.5% of the respondents indicated agreed and 36.2% of strongly agree to question 4.4b; question 4.4c recorded 50.0% agreed and 31.5% strongly agreed, while 14.6% of neutral; 54.6% of the respondents chosen agreed and 29.9% strongly agreed and 13.1% neutral. The feedback within this construct shows that the majority of the respondents agreed that the existing AM facilities at the selected universities in SA are accessible and very useful for both students and academics, although the 'neutral' responses within this construct are also high and this indicates that some respondents did not fully agree with the questions.

In sub-section 4 questions, the highest standard deviation (SD) occurred to questions in the third construct, which are 4.4a, 4.4b, 4.4c, and 4.4d with SD of 0.718, 0.779, 0.782, and 0.787 respectively. This was due to high numbers of neutral responses received for these questions.

Table 7. 11: AM In-House Facilities related questions and respondents' responses (per construct)

AM IN-HOUSE FACILITIES – SUB-SECTION 4								
Likert Scale: 1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree; 5. Strongly Agree								
Construct 1: *Acquisition of in-house AM facilities & establishment of 3D printing Lab*		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M (%)	SD (%)
4.1	Acquisition in-house AM/3D printing facilities at the university fosters:							
4.1a	Effective additive manufacturing education	0	1.5	4.6	51.5	42.3	4.35	0.644
4.1b	Effective additive manufacturing research	0	1.5	4.6	54.6	39.2	4.32	0.635
4.2	Establishment of AM/3D printing labs at the university would increase students' interest in AM or 3D printing technology	0	0	4.6	55.4	40.0	4.35	0.569
Construct 2: *Cutting-edge AM/3D printing facilities at the university*								
4.3 A cutting edge in-house AM/3D printer facilities at our university supports:								
4.3a	Teaching	0	1.5	7.7	58.5	32.3	4.22	0.647
4.3b	Learning	0	2.3	6.9	60.0	30.8	4.19	0.660
4.3c	Academic research	0	0.8	3.8	60.0	35.4	4.30	0.579
4.3d	Industry collaboration	0	0	4.6	56.9	38.5	4.34	0.565
Construct 3: *Effectiveness of available/existing AM facilities*								
4.4	In-house AM facilities at selected universities in South Africa are available for students and academics:							
4.4a	For design and prototyping purposes	0	2.3	10.0	50.8	36.9	4.22	0.718
4.4b	For final product printing purposes	0	3.8	11.5	48.5	36.2	4.17	0.779
4.4c	For teaching and research activities (i.e. master's and PhD students research)	0	3.8	14.6	50.0	31.5	4.09	0.782
4.4d	For final or fourth year projects	0	5.4	13.1	54.6	26.9	4.03	0.787

RELIABILITY FOR AM IN-HOUSE FACILITIES – SUB-SECTION 4			
Construct 1	Internal reliability: Cronbach alpha = 0.850	Average inter-item correlation = 0.654	N of Items = 3
Construct 2	Internal reliability: Cronbach alpha = 0.822	Average inter-item correlation = 0.542	N of Items = 4
Construct 3	Internal reliability: Cronbach alpha = 0.839	Average inter-item correlation = 0.565	N of Items = 4

Source: Researcher's own construction

- **7.5.4.2 Inter-item correlation matrix for sub-section 4 questions – AM In-House Facilities**

The inter-items correlation matrix for questions in sub-section 4 were divided into three constructs as indicated in Appendix E. The correlation coefficients are expected to be statistically significant at the level of 5%. Therefore, the inter-item correlation matrix for construct 1, 2 and 3 are statistically significant at the level 0.7, 0.5 and 0.5 respectively (Piedmont, 2014). The inter-item correlation matrix for questions in sub-section 4 contained no negative values, which shows that all the items measured same underlying characteristics (Pallant, 2011). Table 7.12 shows the component correlation matrix for the three constructs in sub-section 4. The relationship between the first and second constructs considered to be 'medium' with correlation coefficient of 0.303, which implies that there is practically visible relationship. The relationship between second and third construct regarded to be 'small' with correlation coefficient of 0.165 and this indicates no practical significant relationship.

Table 7. 12: Component correlation matrix for sub-section 4 questions

Component	1	2	3
1	1.000	0.303	0.421
2	0.303	1.000	0.165
3	0.421	0.165	1.000

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

7.5.5 Sub-section 5 – AM Research and Development (R&D)

The questions in sub-section 5 focused on *research and development (R&D)* from an AM perspective. The aim of this sub-section is to examine the importance of R&D in promoting AM technology in the education sector. This sub-section contained 4 questions (i.e. 5.1 to 5.4). Question 5.1 were divided into 3 sub-questions (5.1a – 5.3c) and in this case, a component matrix was conducted which shows only one grouping and therefore, it contains only one construct as shown in Table 7.13.

Table 7. 13: Component matrix[a] for questions in sub-section 5

Component Matrix[a]

Component	1
B5.1a	0.688
B5.1b	0.725
B5.1c	0.713
B5.2	0.800
B5.3	0.756
B5.4	0.698

Extraction Method: Principal Component Analysis.
a. 1 components extracted.

- **7.5.5.1 Discussion and interpretation of sub-section 5 questions**

This section contained the general descriptive statistic for questions in sub-section 5 as shown in Table 7.14. The construct exhibited an internal reliability of 0.824 Cronbach alpha based on the analysis of 130 valid responses and the Cronbach alpha are considered acceptable reliability coefficients (Nunnally and Bernstein, 1994). The Kaiser-Meier-Olkin (KMO) for this sub-section is 0.812 which measures the sample adequacy and exceeds the ‘acceptable good value’ of 0.70. To test if the correlations between items are high enough, the Bartlett's test of sphericity is approx. chi-square 262.779 and reached statistical significance of ($p < 0.000$). Also, Table 7.14 presents the frequency percentage, mean (M) and standard deviation (SD) based on the feedback from the respondents.

The questions within this construct centred on *the contributing factors towards effective research and development in AM*. The majority of the respondents show their level of agreement to questions in this construct; although, questions 5.1a, 5.1b, and 5.2 have high ‘neutral’ responses which indicates that some respondents do not fully support the questions. Question 5.1a received 59.9% agreed, 26.2% strongly agreed and 15.4% neutral; question 5.1b recorded 59.2% agreed, 26.2% strongly agreed and 14.6% neutral; questions 5.1c shows 63.1% agreed and 29.2% strongly agreed. 54.6% of the respondents indicated agreed, 30.0% strongly agreed and 15.4% neutral to question 5.2, which implies that majority of the respondents agreed that inclusion of an MSc programme in AM will further strengthen research and development of AM at the universities. 53.8% of the respondent chosen agreed and 39.2% strongly agreed to question 5.3 and 46.9% of the respondents selected agreed and 48.5% strongly agreed to question 5.4. This shows that most of the respondents agreed that sufficient funding is the key contributing factor to promote research and development in AM technology within the universities.

Based on a significant number of positive responses to question 5.2 as relating to “inclusion of MSc program in Additive Manufacturing”. Therefore, this study proposed that a postgraduate program (i.e. MSc or M.Eng) in Additive Manufacturing should be introduced to selected South African universities offering engineering degree or University of Technology to further strengthen the research activities in the field of AM and which in return increase number of AM personnel/professionals.

Table 7. 14: AM Research and Development related questions and respondents' responses (per construct)

AM RESEARCH AND DEVELOPMENT (R&D) – SUB-SECTION 5								
Likert Scale: 1. Strongly Disagree; 2. Disagree; 3. Neutral; 4. Agree; 5. Strongly Agree								
Construct: ***Contributing factors towards effective Research and Development (R&D) in AM***		1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	M (%)	SD (%)
5.1	Advancement of AM; Research and development is playing vital roles:							
5.1a	In the creation of additive manufacturing standards (ISO/ASTM)	0	1.5	15.4	56.9	26.2	4.08	0.689
5.1b	For registration of additive manufacturing patent	0	0	14.6	59.2	26.2	4.12	0.630
5.1.c	For innovative and technological advancement of AM	0	0	7.7	63.1	29.2	4.22	0.570
5.2	Inclusion of an MSc program in Additive Manufacturing at selected universities in South Africa would further strengthen AM Research and development at the universities/industries.	0	0	15.4	54.6	30.0	4.15	0.660
5.3	Annual fund and grant from the Department of Science and Technology (DST) would boost AM research output at various universities in South Africa.	0	0	6.9	53.8	39.2	4.32	0.600
5.4	Annual fund and grant from National Research Foundation (NRF) increase AM research output at various universities in South Africa.	0	0	4.6	46.9	48.5	4.44	0.584
RELIABILITY FOR AM RESEARCH AND DEVELOPMENT – SUB-SECTION 5								
Construct	Internal reliability: Cronbach alpha = 0.824		Average inter-item correlation = 0.439			N of Items = 6		

Source: Researcher's own construction

- **7.5.5.2 Inter-item correlation matrix for sub-section 5 questions – AM Research and Development**

This section presents the inter-items correlation matrix for questions in sub-section 5 as shown in Appendix E. The correlation coefficients are expected to be statistically significant at the level of 5% (i.e. $p > 0.05$). Therefore, the inter-item correlation matrix is statistically significant at the level 0.20 (Piedmont, 2014). The inter-item correlation matrix for questions in sub-section 5 recorded no negative values, which shows that all the items measured same underlying characteristics (Pallant, 2011). In sub-section 5, there is no correlation matrix because only one component was extracted and as a result, the solution cannot be rotated.

7.6 The Summary of Factorial Responses

Table 7.15 below shows the summary of the construct responses with their mean (M) and Standard deviation (SD) based on the analysis of N valid (130) items. Mean is the most widely used in statistical analysis and the research articles. Mean is referred to as the measure of central tendency (Leedy and Ormrod, 2010). In this study, higher value for mean indicates that an answer is closer to a positive feedback (i.e. Agree and Strongly agree). Standard deviation is used to identify the degree of dispersion or the degree to which the scores are evenly distributed

(Struwig and Stead, 2004). High standard deviation implies that the respondents do not view the statements in the same manner.

The questions within the fourth construct in sub-section 1 (AM technology) have the lowest (M of 3.6538), followed by questions in within sub-section 5 (AM Research & Development) with 4.1288 of Mean. The construct with the highest mean occurred with questions within the first construct in sub-section 3 (AM educational curriculum) with 4.4923 of M, followed by questions within third construct of the same sub-section. The overall means of the entire constructs from sub-section 1 to 5 are above 4.000. This implies the responses from the respondents are closer to positive feedback of agreed and strongly agreed. The highest SD occurred within the questions in construct 4 of sub-section 1 (AM Technology) with 0.95498 of SD, followed by questions in construct 3 of sub-section 2 (AM Technology Transfer) with 0.68042 and questions in sub-section 5 (AM R&D) with 0.62972. The lower SD occurred within the questions in the second construct of sub-section 1 (AM Technology) with 0.47822 of SD. The SD for all the constructs were fairly high i.e. ranging from 0.40000 to 0.90000 of SD and this shows that the respondents do not view the questions in the same way.

Table 7. 15: The descriptive statistics showing the summary of the factors and constructs used

Sub-sections in Section B	N	Minimum	Maximum	Mean	Std. Deviation
Sub-section 1 – Construct 1	130	3.14	5.00	4.3110	0.52057
Sub-section 1 – Construct 2	130	2.83	5.00	4.1526	0.47822
Sub-section 1 – Construct 3	130	3.00	5.00	4.1769	0.51850
Sub-section 1 – Construct 4	130	1.00	5.00	3.6538	0.95498
Sub-section 2 – Construct 1	130	2.80	5.00	4.3046	0.58732
Sub-section 2 – Construct 2	130	2.80	5.00	4.1877	0.55893
Sub-section 2 – Construct 3	130	2.50	5.00	4.1462	0.68042
Sub-section 3 – Construct 1	130	3.00	5.00	4.4923	0.57393
Sub-section 3 – Construct 2	130	3.00	5.00	4.3192	0.49807
Sub-section 3 – Construct 3	130	2.67	5.00	4.3462	0.56055
Sub-section 4 – Construct 1	130	2.50	5.00	4.2846	0.59370
Sub-section 4 – Construct 2	130	2.33	5.00	4.3385	0.54113
Sub-section 4 – Construct 3	130	3.00	5.00	4.2615	0.49597
Sub-section 5 – Construct 1	130	2.00	5.00	4.1288	0.62972
Valid N (listwise)	130				

7.7 Open-ended questions responses

To gain more insight from the respondents, two open-ended questions were asked as stated below. Some of the responses could be linked to the five factors contained in section B of the questionnaire.

7.7.1 First open-ended question

Do you think inclusion of Additive Manufacturing education to science and engineering curriculum at South African universities is a good idea?

Out of 130 respondents, only 40 respondents decided to answer this question as expected; 30 respondents put 'YES' as the answer; and 20 respondents put 'N/A' (i.e. not applicable) as the answer and 40 respondents did not answer the question at all. The 'YES' answer in this open-ended question implies that the respondents supported "*the inclusion of AM education/courses in the science and engineering curriculum at South African universities*". The 'N/A' as an answer to the question indicates that the respondents are neutral to the question. Some of the responses from the 40 respondents who completed the first open-ended question looked alike in their construction and to avoid unnecessary repetition of respondents' feedback, only the key feedback was captured and listed in Table 7.16 below:

Table 7. 16: Summary of the key respondents' feedback to the first open-ended question

S/N	Key Summary of the Respondents' Feedback
1.	Yes, I do, I also feel that the arts should not be ignored as innovation happens best when different field collaborate
2.	It is a good idea and it will help students understand AM technology and advanced in this field
3.	Yes, most of the science and engineering students are not being aware of AM technology
4.	There is a need for South African universities to include AM in their educational curriculum
5.	Yes, Inclusion of AM education to STEM education is necessary at this era of Industry 4.0
6.	This is good idea, it will promote AM education and expose students to AM technologies
7.	The inclusion of AM education at SA universities will improve mechanical engineering degree curriculum
8.	Yes, this will greatly provide significant advantage to science and engineering curriculum in SA
9.	I think the inclusion of AM education in the science and engineering curriculum in SA is a good idea towards Industry 4.0 revolution in the country
10.	It will help students, academics and industry professionals to develop interest in AM technology and pursue career in AM
11.	AM education is very important at the universities because of the technological advancement in the world and it will improve students' knowledge of design within the engineering curriculum or degree
12.	To take AM technology into another height in STEM education, its inclusion in the educational curriculum is inevitable
13.	Awareness of AM technology is growing rapidly, and specific AM courses can be developed and include in the educational system at the university and this will increase the awareness of the technology.
14.	AM/3D printing technology has been identified as a potential game changer for Industry 4.0 and preparing graduate that will take over the AM industry is essential, and inclusion of AM education in STEM curriculum is a good idea.
15.	Yes, the education aspect of the technology will encourage students to do critical thinking and will attract more students to study STEM courses and career.
16.	I think inclusion of AM education is a good idea but should start at a much lower educational level; for example, early high school.
17.	Yes, inclusion of AM education will enhance the knowledge and understanding of engineering principles in the industry
18.	Yes, to include AM education is a good idea, but it must be within the South Africa STEM education context
19.	My fourth-year project is on AM technology and if such technology can be included in the SA education curriculum, it will go a long way in assisting fourth years' student to carry out research in AM field

20.	If AM education can be incorporated into STEM education in SA, it will be a good achievement for SA universities.
21.	Yes, it will give students an idea of what is really happening in the AM industries when AM courses are part of university curriculum.
22.	Yes, inclusion of AM education will make student compete with other countries not just technology but production and economic growth as well.
23.	Yes, it is a good idea and it makes the learning process to be easy and understandable.
24.	Yes, inclusion of AM education will assist students to keep up with the changing of technology in the world.
25.	Yes, AM education will provide students with knowledge of AM and these will assist undergraduate and postgraduate in working project or research related to AM.
26.	Yes, I didn't have an idea of what AM mean, until I started working at the VUT. The students in the university need exposure to AM in order to gain knowledge and interest in AM and before getting to the industry
27.	Yes, from my personal point of view, I have noticed that most of the students who visit our AM lab have no idea or little knowledge of what AM technology and inclusion of AM education in the university's STEM curriculum will be good.
28.	Yes, because both undergraduate and postgraduate students needed exposure AM technology
29.	Yes, inclusion of AM course is the only platform to introduce AM education to the South African university
30.	Yes, for SA government to benefit from their investment on AM technology, there is a need to introduce AM education in the STEM educational system in SA.

Source: Researcher's own construction

The summary of the respondents' feedbacks as shown in Table 7.16 provides respondents' views as relating to the inclusion of AM education in the science and engineering curriculum in South Africa. The feedback provides more insight into the first open-ended question and these can also be linked to the five sub-sections in the section B of the questionnaire. The overall or summary of the respondents' feedback shows that the inclusion of AM education in the education curriculum at the SA universities would:

1. Allow collaboration with other fields;
2. Increase AM awareness;
3. Enhance STEM education;
4. Assist toward the actualization of industry 4.0;
5. Increase in the number of AM personnel/professional;
6. Encourage people to pursue career in AM;
7. Improve students' engineering drawing skills;
8. Expose people to AM and
9. Promote technological advancement of AM.

Therefore, based on the benefits highlighted above as relating to the inclusion of AM education in the educational curriculum at the South African universities. This study proposed that AM education should be included in the science and engineering curriculum at the South African universities to promote AM education and enhance effective research and development (R&D) in the field of AM as this is very crucial in this era of Industry 4.0.

7.7.2 Second open-ended question

Does the "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Centre" or the 3D printing Lab at your university is ***having positive impacts*** *on Additive Manufacturing education or* ***Promoting AM*** *education?*

In the second open-ended question, out of 130 respondents that participated in the survey, only 45 respondents chose to answer the question; 45 respondents wrote 'Yes' as their answer to the question; 10 respondents written 'N/A' as their answer and 30 respondents did not attempt to answer the question at all. As earlier mentioned in the first-open-ended question, the 'YES' answer implies that the respondents supported or agreed with the questions that "*3D printing lab at the university is having impact on AM education or promoting AM education"*. The 'not applicable' (N/A) as an answer to the question shows that the respondent is very neutral to the question. Some of the responses from the 45 respondents that willingly completed the question look alike in their construction and to avoid unnecessary repetition of responses. The key feedback from the respondents were stated in the Table 7.17.

Table 7. 17: Summary of the key respondents' feedback to the second open-ended question

S/N	Key Summary of the Respondents' Feedback
1	It is making great impact on AM education and assisting student to build career path in AM.
2.	The Idea 2 Product at VUT is making positive impact and promoting AM knowledge among interested students
3.	The NWU Pukke 3D printing centre assist students to bring their creative thinking into reality, therefore the lab is making positive impact.
4.	The 3D printing facilities at our university is making positive impact and enhancing students' innovative skills
5.	The AM facilities at the lab provide excellent hands-on-experience of AM technology to students
6.	The 3D printing lab is helping postgraduate student to carry out innovative and technological research in AM
7.	The 12P lab at VUT assisted students with different design projects but the I2P lab can be expanded to accommodate more students
8.	The 3D printing lab at the university is having great impact on student and making student to "think additive", i.e. to be innovative and creative in thinking.
9.	The 3D printing lab at the NWU is changing the teaching and learning perspective of the students as the students engaging in design of prosthetic and other complex design.
10.	The 3D printing lab at VUT has introduced many students into the fundamental knowledge of AM
11.	The positive impact of Idea 2 Product lab at VUT is overwhelmingly as more people has gained knowledge about AM technology, but more AM facilities and AM personnel are still needed.
12.	My advice is that such I2P lab should be established on every university campus in SA because of its positive impact on students.
13.	The 3D printing lab is having positive impact on AM education and it is preparing tomorrow engineers and scientist to take over the manufacturing workforce challenges and provide solution.
14.	An in-house AM equipment is an essential aspect to promote AM education at the university, at my university, there are no 3D printing lab for students' use per se, it would be good is such 3D printing lab like I2P can be established here
15.	As more AM personnel and graduate with knowledge of AM is needed globally, establishment of AM lab such as I2P lab will increase the potentiality of student developing interest in AM.

16.	The 3D printing lab is very useful for engineering students because people are getting expose to AM technology and becoming sound technological.
17.	AM lab has enabled students to change their view of engineering drawing and design in a more positive way.
18.	The AM lab helps students to practice what they learn in theory using the available AM facilities at the university
19.	The I2P lab is making significant impact in the life of willing students because the lab is accessible to everyone irrespective of your course of study.
20.	The 3D printing lab is having positive impact on students but most of the lab are equipped with entry-level 3D printing machines, high-end industrial AM machines should be introduced to the laboratory as well.
21.	The 3D printing lab impact can be felt on science and engineering education through effective use of CAD software by the students most especially among mechanical engineering degree.
22.	The use of 3D printing facilities by the students has promote effective team work on design assignment or project
23.	The lab contained entry-level 3D printers for teach basic AM technology and through this platform students are being equipped to develop mind-set to advance their career to operate high-end AM machines.
24.	The AM lab at our university comprises of fewer entry-level 3D printers for use of students and staffs; the lab is contributing meaningful to the advancement of AM education, but more 3D printers are needed to take more people.
25.	The AM/3D printing lab allows first years to develop interest in AM and grow to become an AM expert at their fourth year/postgraduate level; the primary aim of AM lab and to promote AM education at the university.

Source: Researcher's own construction

The summary of the feedback from the respondents in Table 7.17 shows how the existing AM/3D printing lab is making positive impact and promoting AM education at the universities. Some of the responses show that the need to establish more AM laboratories across all universities. The overall summary or responses of the respondents to the second-open-ended questions show that the available AM/3D printing lab at the university is:

1. Assisting students to building career in AM;
2. Improving students' engineering drawing skills,
3. Providing students with fundamental knowledge of AM;
4. Equipping students with the ability to work as a team on project and research;
5. Promoting innovative and technological research in AM;
6. Increasing AM personnel or graduate in the field of AM.

Therefore, based on the respondents' feedback to the question on the availability of AM lab at the universities and the benefits highlighted above. This study proposed that AM laboratory should be launched at various universities to rapid growth of AM education and promote efficient AM technology knowledge transfer across different field.

7.8 Summary of the Cronbach's alpha (α) coefficient, average inter-item correlation, kaiser-meier-olkin and bartlett's test of sphericity of all factors

The condition for rejecting and accepting Cronbach's alpha (α) was explained in chapter 6 section 6.8.3. Cronbach's alpha (α) is used to measure the internal reliability or internal consistency and it is an indication that the questionnaire has ability to measure the construct or factors in question. The acceptable Cronbach's alpha ranges from 0.6 to 0.8 and Cronbach's alpha from 0.9 indicates high reliability. Therefore, the overall Cronbach's alpha for all the constructs or factors in the questionnaire are considered acceptable from 0.615 to 0.883 as shown in Table 7.18 and this indicates that all the Cronbach's alpha values have 'relatively high internal consistency' (Nunnally and Bernstein, 1994).

The average inter-items correlations values show the degree of relationship between the factors. The lowest average inter-item correlation occurred within the second and third constructs of sub-section 1 (0.351 and 0.328), while the highest average inter-item correlation occurred second construct of sub-section 3 (0.704). The overall average inter-item correlation shows strong inter-item relationship. To identify if Kaiser Meier Olkin measure the sample adequacy, this guideline needs to be considered [<0.5: not acceptable; 0.5 – 0.7: medium; 0.7 – 0.8: good; 0.8 – 0.9: very good; >0.9: superb]. The Kaiser Meier-Olkin for the overall constructs or factors in the questionnaire are between 0.746 to 0.812 which shows that it measures the sample adequately and exceeds the acceptable good value of 0.70. The overall Bartlett's test of sphericity for the constructs or factors show that the correlations between the items are higher enough which reached the statistically significant of ($p < 0.000$).

Table 7. 18: Summary of the Cronbach's alpha, average inter-item correlations, KMO and Bartlett's test of sphericity.

AM Framework Factors/Variables	Internal reliability: Cronbach Alpha	Average Inter-item Correlations	N of Item	Kaiser-Meier-Olkin (KMO)	Bartlett's test of sphericity (approx. chi-square)
1. AM Technology					
Construct 1 – Applications/usefulness of AM Technology	0.853	0.463	7	0.788	1102.310 – p < 0.000
Construct 2 – Importance and advantages of AM technology	0.762	0.351	6	0.788	1102.310 – p < 0.000
Construct 3 – Present and future impacts of AM technology on science and engineering education	0.657	0.328	4	0.788	1102.310 – p < 0.000
Construct 4 – Accessibility and acquisition of fundamental knowledge of AM technology	0.872	0.696	3	0.788	1102.310 – p < 0.000
2. AM Technology Transfer					
Construct 1 – Aim, roles & importance of technology transfer	0.883	0.603	5	0.746	915.226 – p < 0.000

Construct 2 – Benefits of University-Industry collaboration in AM technology transfer.	0.840	0.530	5	0.746	915.226 – $p < 0.000$
Construct 3 – Involvement of 3D Printing service bureau or company in AM technology transfer	0.615	0.482	2	0.746	915.226 – $p < 0.000$
3. AM Educational Curriculum					
Construct 1 – Need for more AM personnel in the field of AM	0.827	0.544	4	0.761	595.237 - $p < 0.000$
Construct 2 – Inclusion of AM education/courses in science and engineering curriculum	0.870	0.704	3	0.761	595.237 - $p < 0.000$
Construct 3 – Suitability of entry-level 3D Printer for AM education.	0.695	0.542	2	0.761	595.237 - $p < 0.000$
4. AM In-House Facilities					
Construct 1 –Acquisition of in-house AM facilities & establishment of 3D printing lab	0.850	0.654	3	0.785	671.181- $p < 0.000$
Construct 2 – Cutting-edge Am/3D printing facilities at the university	0.822	0.542	4	0.785	671.181- $p < 0.000$
Construct 3 – Effectiveness of the available/existing AM facilities	0.839	0.565	4	0.785	671.181- $p < 0.000$
5. AM Research and Development (R&D)					
Construct – Contributing factors towards effective research and development (R&D) in AM	0.824	0.439	6	0.812	262.779 - $p < 0.000$

Source: Researcher's own construction

7.9 Stated hypotheses for this study

This study uses a quantitative approach, the null hypotheses (H_0) and alternative hypotheses (H_1) were listed below based on five factors/variables stated in the questionnaire.

- **AM Technology**

(H_0) Additive manufacturing technology ***is*** enhancing the science and engineering education at the universities and having positive impacts across many industries.

(H_1) Additive manufacturing technology ***is not*** enhancing the science and engineering education at the universities and ***not*** having positive impacts across many industries.

- **AM Technology Transfer**

(H_0) Technology transfer ***is*** playing a significant role in promoting AM education and creates an enabling environment for university-industry collaboration.

(H_1) Technology transfer ***is not playing*** a significant role in promoting AM education and ***does not*** create an enabling environment for university-industry collaboration.

- **AM Educational Curriculum**

(H_0) Inclusion of AM education curriculum at the university ***is necessary*** to increase AM personnel/professionals; to strengthen students' interest and create career path in AM

(H_1) Inclusion of AM education curriculum at the university **is not necessary** to increase AM personnel/professionals; to strengthen students' interest and create career path in AM.

- **AM In-House Facilities**

(H_0) Availability of cutting-edge additive manufacturing facilities ***would*** promote effective AM education and advance AM research activities at the universities.

(H_1) Availability of cutting-edge additive manufacturing facilities ***would not*** promote effective AM education and advance AM research activities at the universities.

- **AM Research and Development (R&D)**

(H_0) Research and development ***creates*** room for innovative and technological advancement in AM through various funding from different government bodies (e.g. DST, NRF, etc.).

(H_1) Research and development ***does not create*** room for innovative and technological advancement in AM through various funding from different government bodies (e.g. DST, NRF, etc.).

7.10 Hypothesis Testing

As earlier described in Chapter 6, hypothesis testing is regarded as the vital belief in statistical analysis. Hypothesis is totally based on 'Null' and 'Alternative' hypotheses and to properly test for hypothesis in a study, certain sets of statistical knowledge parameter is needed such as [confidence intervals, effect size, statistical significance (*P*), sample size requirement, P-value and etc.]. A true hypothesis would be accepted if the observed data do not differ from what is expected based on chance alone. A null hypothesis is evaluated based on chance while an alternative hypothesis is referred to as a complement of the null hypothesis (Zaiontz, 2015).

A null hypothesis is represented by $H_{0,}$ while an alternative hypothesis is represented by H_1, ***which mean that H_0 is true if and only if H_i is false.*** Irrespective of the alpha level, the hypothesis is tested based on two outcomes (Martz, 2013) as illustrated below:

- **Reject null hypothesis**: If the statistical significance is (p-value <= 0.05), this implies that there is a statistical significant difference between the means. Therefore, it can be concluded that "*the alternative hypothesis is true at the 95% confident interval/level".*

- **Fail to reject the null hypothesis**: if the statistical significant is (p-value >0.05), this implies that there is no statistical significant difference between the means. Then, it can be concluded that "*no enough evidence is available to suggest the null is false at the 95% confidence interval".*

In testing hypothesis, p-value is typically used to decide if the data support the null hypothesis or not, but in situation where the P-value is extremely low (i.e. below 0.05), from a statistician's point of view "the null hypothesis must go or rejected" (Martz, 2013).

In this study, the hypothesis was based on a 'two tailed significant testing' and the t-Test was carried out in relation to the gender of the respondents as shown in Table 7.19. An accepted significant level for two tailed hypotheses is alpha (α) = 0.05 and the two tailed hypotheses testing is based on $H_{0:}$ P = alpha and $H_{1:}$ $P \neq$ alpha.

Table 7. 19: Summary of t-Test for based on Gender

AM Framework Factors/Variables	Gender	N	Mean	Std. Deviation	Significance Level (*P*) (Two-Tailed)	Effect Size
1. AM Technology						
Construct 1	Male	73	4.3307	0.53180	0.627	0.085
	Female	57	4.2857	0.50939		
Construct 2	Male	73	4.2078	0.49362	0.137	0.255
	Female	57	4.0819	0.45220		
Construct 3	Male	73	4.2568	0.51534	0.046	0.354
	Female	57	4.0746	0.50877		
Construct 4	Male	73	3.7215	0.91627	0.363	0.154
	Female	57	3.5673	1.00389		
2. AM Technology Transfer						
Construct 1	Male	73	4.3288	0.57191	0.598	0.090
	Female	57	4.2737	0.61019		
Construct 2	Male	73	4.1671	0.54976	0.637	0.082
	Female	57	4.2140	0.57428		
Construct 3	Male	73	4.1370	0.67834	0.863	0.030
	Female	57	4.1579	0.68893		
3. AM Educational Curriculum						
Construct 1	Male	73	4.4658	0.57932	0.553	0.105
	Female	57	4.5263	0.57025		
Construct 2	Male	73	4.3219	0.47777	0.945	0.012
	Female	57	4.3158	0.52722		
Construct 3	Male	73	4.3470	0.58118	0.984	0.003
	Female	57	4.3450	0.53809		
4. AM In-House Facilities						
Construct 1	Male	73	4.3356	0.59544	0.269	0.195
	Female	57	4.2193	0.59023		
Construct 2	Male	73	4.2968	0.56536	0.322	0.168
	Female	57	4.3918	0.50835		
Construct 3	Male	73	4.2808	0.48760	0.618	0.086
	Female	57	4.2368	0.50977		
5. AM Research and Development (R&D)						
Construct	Male	73	4.1541	0.65964	0.607	0.087
	Female	57	4.0965	0.59341		
Note: **Confidence Interval of the Difference was 95%**						

Source: Researcher's own construction

7.10.1 The Summary of the "Accepted" and "Rejected" Null Hypotheses

The null' and 'alternative' hypotheses for the five AM factors were stated in section 7.10 above. The AM framework factors comprise of (AM technology, AM technology transfer, AM educational curriculum, AM in-house facilities and AM research and development). To test for the hypothesis, the significant *P*-value was used to determine where the data supported the null hypothesis or not as shown in Table 7.20. The null hypothesis will be accepted when the P (α) value >= 0.05 and rejected when P (α) value <=0.05. From Table 7.20, all the significant *P* values were > than α =0.05. Therefore, all the null hypotheses (H_0) were ***accepted,*** and all the alternative hypotheses (H_1) were ***rejected.***

Table 7. 20: The outcomes of the hypotheses testing

The Outcomes of the Hypotheses Testing				
AM Framework Factors/Variables	**The Significant (*P*)**	**Null Hypothesis (H_0)**	**Alternative Hypothesis (H_1)**	**Effect Size**
1. AM Technology				
Construct 1 – Applications/usefulness of AM technology	*P* (0.627) value > 0.05	**Accepted**	**Rejected**	0.085
Construct 2 – Importance & advantages of AM technology	*P* (0.137) value > 0.05	**Accepted**	**Rejected**	0.255
Construct 3 – Present & future impacts of AM technology on science and engineering education.	*P* (0.046) value > 0.05	**Accepted**	**Rejected**	0.354
Construct 4 – Accessibility and acquisition of fundamental knowledge of AM technology.	*P* (0.363) value > 0.05	**Accepted**	**Rejected**	0.154
2. AM Technology Transfer				
Construct 1 – Aim, roles and importance of technology Transfer.	*P* (0.598) value > 0.05	**Accepted**	**Rejected**	0.090
Construct 2 – Benefits of University-Industry collaboration in AM technology transfer.	*P* (0.637) value > 0.05	**Accepted**	**Rejected**	0.082
Construct 3 – Involvement of 3D Printing service bureau or company in AM technology transfer.	*P* (0.863) value > 0.05	**Accepted**	**Rejected**	0.030
3. AM Educational Curriculum				
Construct 1 – Need for more AM personnel in the field of AM.	*P* (0.553) value > 0.05	**Accepted**	**Rejected**	0.105
Construct 2 – Inclusion of AM education/courses in science and engineering curriculum.	*P* (0.945) value > 0.05	**Accepted**	**Rejected**	0.012
Construct 3 – Suitability of entry-level 3D Printer for AM education.	*P* (0.984) value > 0.05	**Accepted**	**Rejected**	0.003
4. AM In-House Facilities				
Construct 1 –Acquisition of in-house AM facilities & establishment of 3D printing lab.	*P* (0.269) value > 0.05	**Accepted**	**Rejected**	0.195
Construct 2 – Cutting-edge Am/3D printing facilities at the university.	*P* (0.322) value > 0.05	**Accepted**	**Rejected**	0.168
Construct 3 – Effectiveness of the available/existing AM Facilities.	*P* (0.618) value > 0.05	**Accepted**	**Rejected**	0.086
5. AM Research and Development (R&D)				
Construct – Contributing factors towards effective research and development (R&D) in AM	*P* (0.607) value > 0.05	**Accepted**	**Rejected**	0.087
Note: Confidence Internal of the Difference was 95% **For two tailed hypotheses testing H_0: *P* = alpha and H_1: *P* ≠ alpha. If *P*-value <=0.05, H_0 is rejected and If *P*-value >= 0.05, H_0 is accepted.**				

Source: Researcher's own construction

Therefore, the following five null hypotheses (H_0) were accepted because there are significant numbers of positive responses from the respondents towards each factor/variable.

- **AM Technology -** *Additive manufacturing technology is enhancing the science and engineering education at the universities and having positive impacts across many industries.*
- **AM Technology Transfer -** *Technology transfer is playing a significant role in promoting AM education and creates an enabling environment for university-industry collaboration.*
- **AM Educational Curriculum -** *Inclusion of AM education curriculum at the university is necessary to increase AM personnel/professionals; to strengthen students' interest and create career path in AM.*
- **AM In-House Facilities -** *Availability of cutting-edge additive manufacturing in-house facilities would promote effective AM education and advance AM research activities at the universities.*
- **AM Research and Development (R&D) -** *Research and development create room for innovative and technological advancement in AM through various funding from different government bodies (e.g. DST, NRF, etc.).*

Table 7.20 also presents the effect size which was based on the frequency (N), Mean (M) and Standard deviation (SD) for two groups, i.e. the male and female, statistical value (*t* of *F*), the degree of freedom (*df*), significant test (*P*) and 95% of confidential interval. Effect size is used measure the magnitude of an effect based on standardized effect size as shown in Table 7.21. The Cohen's *d* is mostly used to measure effect size (Zaiontz, 2015).

Table 7. 21: The standardized effect size

S/N	Effect Size – Cohen's *d*	Standard Effect Size	Percentage of Variance
1	*d = 0.20*	Small effect	1%
2	*d = 0.50*	Medium effect	10%
3	*d = 0.80*	Large effect	25%

The effect size for all the constructs or factors are $P \geq 0.05$ and while constructs have P<= 0.05. The Cohen's effect suggested that effect size with less 0.20 has small effect size. The effect size for the majority of the constructs indicated low practical significance which implies that there was no difference between the male and female responses. On the other hand, some of the constructs shows high practical significance which implies there are difference between the male and female responses. The descriptive statistics for **skewness** and **kurtosis** of the data could be found in Appendix C. The skewness can be grouped either as highly skewed or moderately skewed distribution because the skewness is less than -1 and greater +1, and also between -0.5 and +0.5 (Gibilisco, 2012). The kurtosis is not a normal distribution because the kurtosis for the constructs contained >3 and <3 (Westfall, 2014).

7.11 Chapter Summary

This chapter has presented the discussion and interpretation of the statistical analysis based on the data collected using a structured questionnaire. The statistical analysis was conducted by NWU statistical consultation services based on 130 completed questionnaires by the respondents. The biographical section and the main section of the questionnaire were properly analysed using relevant statistical methods. For the measuring instrument, an internal reliability test was used, involving a standardized Cronbach's alpha and the stated hypotheses were tested and all the null hypotheses were accepted using the Significant *P* value. The two open-ended questions were analysed, and the significant insight gained from respondents' feedback were stated.

The next chapter presents the main aim of this doctoral study which is to develop a proposed framework for additive manufacturing education – a case study of South African universities. The next chapter presents the factors used in the development of the framework and supporting factors/characteristics that are necessary for a successful AM education implementation at the university level. Lastly, the next chapter also presents the techniques applied in the verification and validation of the results (i.e. the AM education framework).

Chapter 8

8. Development of the Proposed Framework for Additive Manufacturing Education

This chapter presents the development of a proposed framework for additive manufacturing education at the university. The factors considered in the framework were identified through a comprehensive literature review. Selected South African universities were used as the case study for this study. Each of the factor used in the proposed framework for AM education have sub-factors/characteristics that are necessary for a successful AM education implementation at the university. More so, this chapter states the criteria for verification and validation of result as stated by North-West University Faculty of Engineering document. The techniques used in carrying out the verification and validation of this study results are presented in this chapter.

8.1 Proposed framework for effective Additive Manufacturing education

Different sources of literature have been reviewed and show that there is no specific framework for additive manufacturing education presently. However, as earlier stated in section 2.2 of chapter 2, Ga and Hart (2016) developed a framework specifically for teaching the fundamentals of AM to enable rapid innovation using Massachusetts Institute of Technology as the case study and the framework centred on the development of a 14 weeks courses for teaching AM both at the graduate and advanced undergraduate level. Also, Mellor (2014) proposed a conceptual framework for AM implementation which comprises of five factors. The two frameworks developed by Ga and Hart (2016) and Mellor (2014) are not directly related to a framework for AM education at the university.

The aim of this study is to develop a framework for effective AM education using selected South African universities as the case study. Through an extensive literature survey, the researcher was able to identify five factors/variables considered suitable to form a successful AM education framework at the university. The factors include - AM technology, AM technology transfer, AM educational curriculum, AM in-house facilities and AM research and development. These five factors formed the proposed framework for AM education as shown in Figure 8.1.

The five key factors/variables would work together if carefully implemented, that is, AM education cannot exist or be effective without *AM technology* itself; AM *technology transfer* creates an enabling environment for university-industry collaboration to explore the potential of the technology; AM *educational curriculum* serves as the vehicle to introduce AM education at into university educational system; AM *in-house facilities* provide the platform to equip people with both fundamental and advance AM knowledge; and while AM *research and development* promotes innovative and technological advancement in AM through diverse research activities at the university.

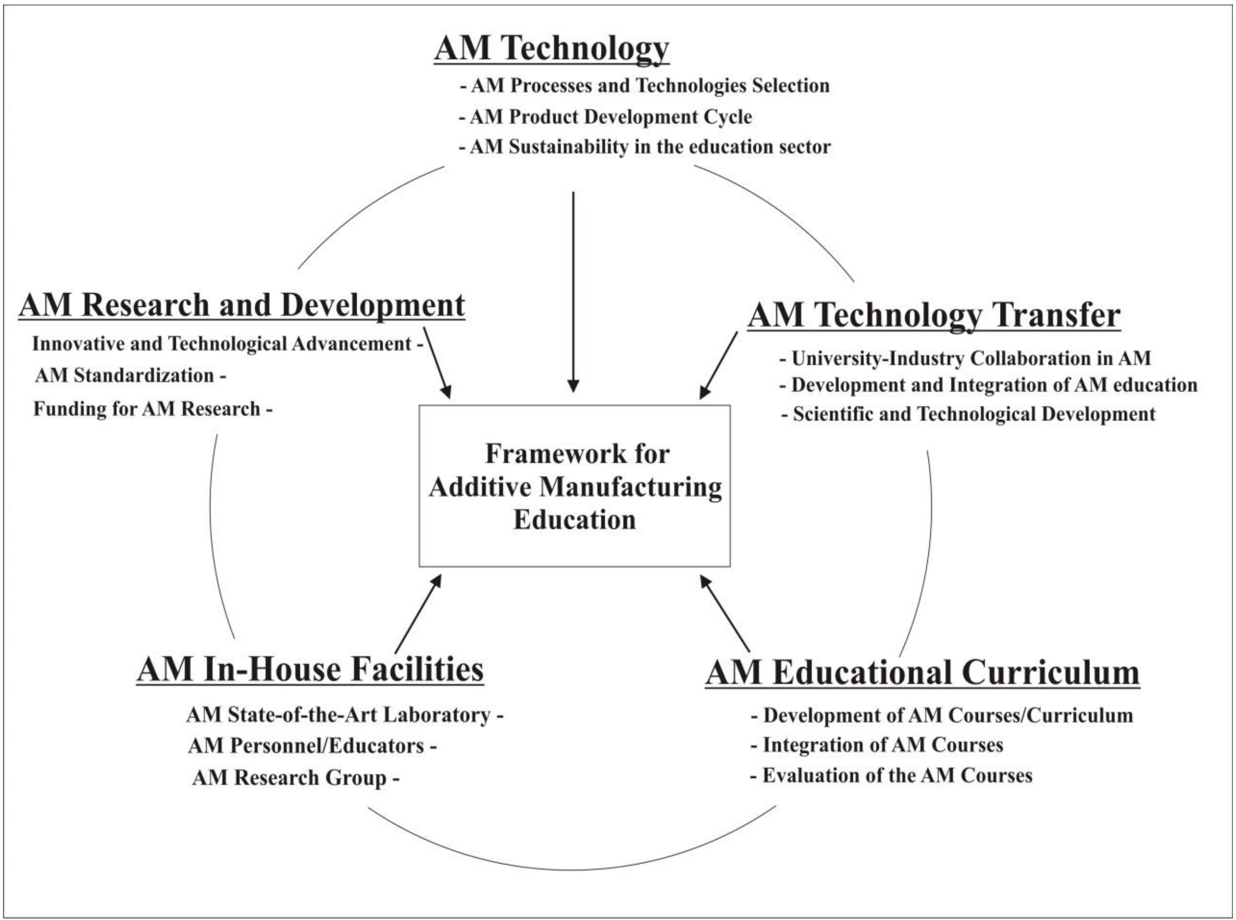


Figure 8. 1: The proposed framework for effective additive manufacturing education

Source: Researcher's own construction.

The next sub-sections discuss the five factors contained in the proposed framework for effective AM education at the university and the supporting factors/characteristics.

8.1.1 AM Technology

The first factor to be considered is the AM technology itself. This forms the most significant factor of the proposed framework for AM education. AM is referred to as the 21st century advanced manufacturing technology. In recent times, more emphasis has been placed on the inclusion of AM technology across all levels of education (i.e. from colleges to universities). Therefore, AM technology will play a significant role in STEM education and there is a need to adapt AM technologies into the engineering and manufacturing education which will serve as a platform to advance AM technology. The three supporting sub-factors described below will assist in the implementation of AM technology at the university.

- **8.1.1.1 AM Processes and Technologies Selection**

Implementation of additive manufacturing technologies could be very challenging and identifying suitable AM technologies for educational purposes could be difficult as well. Most common approaches to teaching and learning using AM/3D printing technology has been [project-based and problem-based learning approaches]. In this case, the choice of AM processes and technology for education purpose should be able to support these learning approaches. This sub-factor will support effective decision-making processes as regarding the types of AM technology a particular university want to consider, which might be different from one university to another. The university needs to consider which kind of research activities they would like to carry out within their AM research group and which type of learning approach they will like to introduce their students to using AM technologies. All these would influence their decision on the types of AM machine to purchase and which AM technologies to consider. Therefore, appropriate AM machines with suitable AM technology will enhance productivity and improve teaching, learning experiences, and the research activities at the university.

- **8.1.1.2 AM Product Development Cycle**

The AM product development cycle is the process of producing 3D printing final product, starting from the design concept to prototype (using CAD software) and production of the final part. Irrespective of the types of AM processes or AM technologies classification chosen, the product development cycle is the same. The product development phase is a fundament aspect of AM technology. In this regard, a suitable AM system for education purposes should be the types that can be easily operated and understood by the students within a short period of time. This would assist AM beginners to develop interest in the technology quickly. For intensive and advanced research purposes, a high-end industrial grade AM machine might be suitable at postgraduate level, while the entry-level 3D printers might be good choice for undergraduate students at the university.

- **8.1.1.3 AM Sustainability**

The sustainability of AM education is a paramount factor to be considered when introducing AM technologies into the education sector. AM technology is a new advanced manufacturing technology that requires feasible sustainability strategy. A long-term sustainability strategy or framework must be put in place in order to support continuous improvement of the AM machines at the university. Some of the factors to be considered in term of the sustainability of AM technology are - electricity cost, regular maintenance of the AM machines, cost of AM materials, continuous training for the AM educators or researchers using the AM technologies, integration of a topic on AM sustainability as part of AM education curriculum. It would be better not to introduce AM curriculum or establish an AM lab at the university if there is no sustainability strategy in place.

8.1.2 AM Technology Transfer

To promote an effective AM education at the university, technology transfer would play an important role. AM technology transfer could serve as a platform to transfer fundamental theoretical knowledge and hands-on experience of AM processes and technologies to wider users, students, academics and industry professionals through wide collaboration between the universities and industrial sector in AM. Therefore, to further promote AM technology in the education sector, technology transfer would serve as one of the vehicles to achieve this task. The following sub-factors or characteristics would help when considering AM technology transfer in the education sector:

- **8.1.2.1 University-Industry Collaboration in AM**

To further enhance and revolutionize the education aspect AM and to prepare graduates for future jobs in AM industry, university-industry collaboration is very essential in this regard. Technology transfer creates an enabling environment to incorporate the students, academics and industry partners in AM together. This will increase industry and university collaboration in AM research, and this will allow students and academics to use industry-based AM machines for research that would be of great benefit to both parties, most especially, in situation where the universities could not afford high-end industrial AM machines, and this would lead to improve product quality and product performance. University-Industry collaboration can also bring potential business opportunities such as mass customization of AM product.

- **8.1.2.2 Development and Integration of AM education**

Development and integration of AM education at the universities require certain levels of expertise both from the university and industry. The university academics can provide theoretical knowledge and certain levels of practical experience, while the industry experts can provide practical insight into AM technology from an industrial perspective. Both university academics and industry experts have significant role to play in developing an effective AM education system at the university. A successful integration of AM education at the university would increase theoretical and practical skills of AM technology for the students.

- **8.1.2.3 Scientific and Technological Development**

Technology transfer promotes scientific and technological innovation in the university and industry. AM technology is still in the infancy stage of development and possible ways to sustain and promote this disruptive technology are through intensive scientific discovery and technological innovation within the education sector. AM is a type of technology that encourages both creative and innovative thinking; the university can serve as platform to instil such thinking in students, academics and industry professions through effective AM education. Therefore, scientific and technological development should be considered as a key factor when introducing AM technology into the education sector in order to have successful AM education framework.

8.1.3 AM Educational Curriculum

Development of a suitable and feasible education curriculum in AM is the most essential part of a framework for AM education. Significant growth in the use of AM/3D printing technology across different sectors have created a high demand for more skilled workforce of scientists, engineers, engineering technologists with proficient knowledge of AM processes to execute 3D design projects from software 3D design to delivery of physical 3D printing part using world-class AM machine. Incorporating AM/3D printing into the Higher Education Institutions curriculum would assist in preparing students/future engineers for a successful career path in STEM education. Therefore, the following sub-factors would contribute to a successful incorporation of AM educational curriculum at the university as stated below:

- **8.1.3.1 Development of AM courses/curriculum**

A significant approach to AM education at the university and a first step to a successful integration of AM educational curriculum is to develop an AM course within the context of the country educational system.

Development of a new course in AM entails some certain knowledge and expertise of AM technology and, in some cases, existing STEM courses can be re-designed to conform to AM curriculum. For effective AM education curriculum at the university, the researcher proposed a sample of a AM educational curriculum that universities or organizations can use as a baseline to implement a good AM curriculum/course at their universities. It will be expected that a good AM education curriculum should include both theoretical (foundational courses) and practical (group or individual projects).

The proposed AM education curriculum or framework would be useful within an engineering context as presented below.

- Introduction to fundamental AM technology – This topic is expected to present an introduction to AM education for beginners. The history of AM will be introduced to the students and the emerging market/AM technology landscape will be presented. This course will introduce the students to Fourth Industrial Revolution (Industry 4.0).
- Application of AM technology – This topic will give the students a broader knowledge of different area of AM applications, for instance, medicals, engineering, automobile, dental, etc. This topic will assist the students to get the business perspective of AM.
- AM technologies and processes – This topic/module will introduce students to different AM processes and technologies. In this course, students will have knowledge of wide range of AM technology.
- Structure of AM technology standards – This topic will broaden the knowledge of students on the importance of standardization in AM. This topic can be taught in accordance with the newly agreed-upon additive manufacturing standards structure which was developed by ISO/TC 261 and ASTM F42 international committee.
- Design for Additive Manufacturing – This topic will introduce students to the fundamental design principle using entry-level CAD software for design. The students will gain both theoretical and practical knowledge of AM designs.
- Introduction to Simulation and Optimization techniques – This topic will expose students to simulation and optimization of 3D printing prototypes, for instance, design and optimization of complex parts.
- Health and Safety of AM lab -This topic introduces students to the health and safety guiding principle when working with entry-level 3D printers or high-end industrial AM machines using state-of-the-art AM laboratory.
- Business processes and supply chain management – This topic introduces the students to the business aspect of AM technology, for instance, business processes and supply chains management.
- Individual and group project – This aspect of the course will involve the students to carry out both individual and group projects. The students will need to bring in their innovative thinking to complete the practical project of the course.

- **8.1.3.2 Integration of AM Course**

Integrating the AM course into the education system, especially the STEM curriculum is another factor to be considered for a successful AM educational framework or implementation. One significant aspect of AM education is to develop an AM course and another crucial aspect is the integration of the course into the existing educational system either as a new AM courses or in addition to an existing STEM course. In this case, an appropriate integration method has to be considered, for instance, if integrating an AM course into the engineering curriculum; design and manufacturing skills is the central focus. This means that the student must understand how 3D printing works, learn how to design objects using some entry-level 3D printing CAD software tools and gain basic repair techniques of 3D printing. Engineering drawing and 3D printing designs would assist the students to improve their engineering skills.

The AM courses can be integrated directly into the education curriculum after careful consideration or selection of relevant course topics. Another technique is that, the integration can be done in parallel with existing STEM curriculum, i.e. AM courses can be introduced gradual into the system by re-structuring one or two existing educational curriculum that are closely related to design and manufacturing.

- **8.1.3.3 Evaluation of the AM course**

To ensure effective AM educational curriculum, progressive evaluation of the courses is very essential; because AM technology is still very new within the educational system. To ensure sustainability of AM education, there is a need to measure the continuous progress of AM curriculum and make appropriate amendment when necessary. Therefore, evaluation of AM course content should be a continuous process to ascertain quality and continuous improvement of AM educational curriculum within the university system.

8.1.4 AM In-House Facilities

There is no institution that can successfully introduce or integrate AM technologies into their education system without state-of-the-art in-house AM/3D printing facilities. Availability of AM/3D printing facilities at the university would determine the level of teaching, learning and research activities in the field of AM. Most developing countries are currently not considering AM education because of unavailability of AM in-house facilities for education and research purposes for instance, few South African universities have in-house AM facilities. The presence of AM equipment in-house at the university would increase cutting edge research activities and enhance STEM education. The following sub-factors or characteristics would help when considering AM in-house facilities within the education sector:

- **8.1.4.1 AM State-of-the-Art Laboratory**

In recent times, some of the AM centres are called “centre of excellence in additive manufacturing”. This shows that excellence is very important in planning an AM/3D printing laboratory. Acquisition of AM facilities require state-of-the-art laboratory in order to promote the use of AM technology at the higher educational institutions. It is essential to establish an AM laboratory that would stimulate students to develop an interest in AM technology and motivate researchers to conduct research in emerging areas of AM. It is one thing to purchase a range of world-class AM facilities, another thing is to have a well-structured modern-day AM laboratory that would bring out the beautiful of the AM equipment. An example of such state-of-the art AM labs in South Africa is the Centre for Rapid Prototyping and Manufacturing (CRPM) at the Central University of Technology and the Additive Manufacturing Unit of Vaal University of Technology Sebokeng Campus.

- **8.1.4.2 AM Personnel/Educators**

Functional AM laboratory requires experienced AM personnel/educators or technologist. Acquisition of state-of-the-art AM equipment is not enough to bring about innovation, but it relies on well-experienced AM experts or AM operators/educators/technologist. In today’s world, many manufacturing industries are finding it very difficult to secure engineering graduates with hands-on experience or fundamental knowledge of AM to take over job positions in the AM field. The main work of AM educator or personnel in AM/3D printing lab is to equip students/academics/professionals with fundamental and advanced knowledge of AM and this will eventually produce more graduates in the field of AM.

- **8.1.4.3 AM Research Group**

One of the main essences of AM in-house facilities at the universities or research institutes is to promote cutting-edge research in the field of AM. A research group consists of a team of researchers or experts in a particular field of research and working together on specific research area. To successfully carry out an efficient research in the field of AM, there is a need to establish a committed research group that will focus on both the basic and advanced research in AM. Some of the researchers in the research group could develop the AM curriculum and strengthen AM teaching. Some universities across United States, Europe, United Kingdom, Asia and South Africa have established AM research group at their university with the aim to focus on emerging research area in AM. To proceed on effective AM education journey at the university, creating an AM research group will play significant factor for future growth of AM education and research activities at the universities worldwide.

8.1.5 AM Research and Development (R&D)

Research and development is a crucial part of many organizations and industries in order to challenge the status quo technologically through innovative products, which eventually led to market expansion and product development. For any university or research institute to make a major breakthrough in a particular field, research and development is very necessary. Additive manufacturing is assisting both small and key business players across different sectors to undertake research and development from the fundamental to intermediate phase which is not possible using conventional manufacturing. The following sub-factors stated below would support effective additive manufacturing R&D program for AM education at the university.

- **8.1.5.1 Innovative and Technological Advancement**

Additive manufacturing is regarded as an innovative technology of the 21st century and complementing various existing technologies. Innovative and technological advancement in AM would allow multidisciplinary research and promote industrial and scientific development. In today's world, AM technology is creating an enabling environment for virtually everyone to '*think additive'*, that is, ability to design quickly based on individual innovative and creative thinking, since "*Real Innovation Comes from Within*" (Makerstation, 2017). When considering AM education at the university, innovation and technological advancement should be at the forefront of the initiative or planning, because this could lead to a new product development to satisfy specific target market which would serves as means of generating fund for the university.

- **8.1.5.2 AM Standardization**

One of the challenges facing AM technology progress is standardization. For additive manufacturing to truly attain its full potential as an advanced manufacturing technology, some widely accepted comprehensive standards need to be developed, otherwise, mass adoption of AM technology would be hindered and that is why effective research and development will be crucial in advancing AM standardization and certification. Therefore, AM standardization should be an essential part of an effective AM education framework at the university.

- **8.1.5.3 Funding for AM Research**

Funding is a strong factor in promoting AM education and research activities at any university. The government funding bodies/agencies or publicly funders from different organizations should serve as the crusader to champion the continuous improvement or progress of AM technology at the university. In South Africa, government agencies such as the Department of Science and Technology, National Research Foundation and Industrial Development Corporation having been very instrumental in the advancement of AM technology both within the educational and industrial sectors. Therefore, government funding bodies/agencies have a key role to play promoting research and development in the field of AM and to provide solid foundation for AM education at the universities worldwide.

8.2 Criteria for validation and verification of research

According to the North-West University guidelines for PhD assessment in engineering, verification and validation are well defined as follows:

Verification refers to "checking / affirming that a proposed solution to a problem is correctly implemented. In the context of a more research orientated project, verification will imply that a proposed analytical approach gives the expected results. It can take the form of using simulation to check the results of the proposed analytical solution. In terms of a more product development type project, verification implies checking whether the design meets the specification. In the case of verification, the proposed analytical solution or the product specification is assumed to be valid".

Validation implies "checking / affirming that the proposed solution to the problem actually solves the problem or is a valid solution. The most common form will be to implement the proposed solution in the context of the actual problem and to check whether the problem is really solved. For a more research orientated problem, validation can imply either practically implementing the proposed solution or comparing the simulated results with actual data. In terms of a more product development type project, validation implies checking whether the specification is correct i.e. does the solution solve the actual real-life problem of the client?"

8.2.1 Verification and Validation of the study

For purposes of this study, verification implies meeting the specification while validation is concerned with whether the particular research specification is met.

In this study, verification means to check if the design meets the specification. This study is a 'Non-Experimental' research that uses literature review, pilot survey, questionnaire – with liker scale and respondents' feedback to approach the development of a framework for AM education at the university. Therefore, this study is regarded as 'product development' type of research based on criteria in section 7.12. The research design meets the research specification that is the aim of the study. The proposed framework for AM education is assumed to be valid based on the statistical processes which is follow by inherently provided verification of the research results.

In this study, validation implies checking if the proposed solution to the problem really addresses the problem or the solution is valid. The research problem shows that there is no specific framework for effective AM education at South Africa universities. The research aim is to develop a framework for AM education as a solution to the problem. This type of study can be referred to as 'product development type of research' as stated in section 7.12 which is also a non-experimental research. In this regard, validation implies to check if the solution solves the real-life problem. Schwerin (2010) stated that "validity of a research can be increased by evaluation and approval of the research results by interviewees, colleagues and experts in the field".

This study uses a questionnaire with a Likert scale and prior to the main data collection, face validity was also conducted on the measuring instrument and an *exploratory qualitative investigation* was conducted; which is also referred to as 'pilot survey' where group of expert in the field of AM check the questionnaire, completed the questionnaire and provided feedback on the questionnaire in the open-ended questions. This enables the researcher to identify relevant ways to improve the questionnaire. The group of experts that provided feedback to the questionnaire consists of the academics (Professors and Senior lecturers, Post-doctoral fellow, doctoral students) and industrial experts in AM, as their names and organizations were listed in the table in Appendix H.

Finally, the structure and content of the framework for AM education was later given to some AM experts within the educational sector to validate it, their feedback shows that the content and structure of the proposed AM education framework is suitable and can be accepted for use at the universities. Their feedback further enhances the re-construction of the questionnaire and increase the credibility and validity framework in this study. The names of the validators would not be listed in this thesis because it is against the ethical guidelines/principles.

Therefore, the specification or the solution provided in this study is assumed suitable for a successful AM education framework/implementation at the university, although South African universities were used as the case study, but the proposed framework for AM education in this study is considered valid and suitable for any universities worldwide considering the inclusion or implementation of AM education into their university systems.

8.3 Chapter Summary

This chapter has presented the proposed framework for additive manufacturing education at the university using South African universities as a case study. The structure and content of the framework has been presented in an appropriate manner. The proposed framework comprises of five factors/variables and each factor has sub-factors as supporting factors/characteristics necessary for successfully AM education implementation at the university. Lastly, this chapter also presented the techniques applied in the verification and validation of the results.

The next chapter presents the conclusions and recommendation for future research. The research aim, and objective will be further review and clarify. The research questions will be checked if it is well answered. The chapter also presents the significant contribution of the study as well as the limitations of the study.

Chapter 9

9. Conclusions and recommendations for future work

The final chapter of this thesis concludes the study by reviewing the research aim, objectives and the research questions and to check if the aim of the study has been met. This chapter also presents the main contribution of the research and the recommendation of the study. The limitations and possible future work that could improve the outcomes of this research also presented.

9.1 Conclusions of the study

This study focuses on additive manufacturing education research. This study uses a measuring instrument (questionnaire) to analyse the participants' perception on the impact of AM technology and the inclusion of AM education at the South African universities. The respondents' feedback has shown that there are significant positive responses that supports the need for a successful framework for AM education. The main aim of this study is to investigate the impact of AM technology at selected South African universities and to develop a framework for effective AM education to further enhance the educational aspect of the AM technology at South Africa universities.

The questionnaires were used to investigate the impact of AM technology and positive responses were recorded from the respondents that shows the impact of AM technology on science and engineering education at the selected South African universities very significant. In section 8.1 of Chapter 8, a proposed framework for additive manufacturing education at the university was presented which consists of five factors/variables identified through literature review and each factor contained three sub-factors or characteristics that would further influence a successful inclusion or implementation AM education at the universities as shown in Figure 8.1. This study carefully followed the research methodology that was presented in Chapter 6 of this thesis which led to development of a framework based on the findings. Therefore, this PhD research has fulfilled the aim of the study.

The five objectives stated in Chapter 1 of this doctoral thesis have been met. Each objective is further reviewed below:

Objective 1: *To conduct a comprehensive literature study on AM education, technologies, its applications in industries, academic; and sustainability of additive manufacturing in education sector.*

The first objective has been met through an in-depth literature survey which provides significant insights into the study. The literature review also assists the researcher to see the gap in research within the AM education research field; which shows that - there is limited research on AM education and presently, there is no specific framework for additive manufacturing education at the universities that could strengthen the inclusion or implementation of AM education at the university." and this led to the identification of the research problem and formulation of the research questions.

This literature review section of this PhD thesis was further divided into four chapters. The second chapter of this thesis focuses on additive manufacturing technology which covers AM processes and technologies, advantages and challenges of AM, history of AM and history of early adoption of AM in South Africa. The third chapter of this study contained the application of AM in the education sectors and this chapter covers extensive review of different AM frameworks, recent research in AM/3D printing education, and AM/3D printing laboratory concept at the universities and a SWOT analysis to evaluate the present and future prospects of AM education and research in South Africa. The fourth chapter contained the applications of AM technology across different sectors and the global perspective of AM applications from aerospace to research and development sectors; and the risk and uncertainty associated with AM technology. The fifth chapter contained the sustainability of AM in educational sector, advantages of AM sustainability, indicators of AM sustainability, sustainability of AM education at the universities and lastly, the importance of standardization to AM education.

Objective 2: *To investigate the existing AM education, framework and curriculum through literature survey from a global perspective.*

The second objective has been fulfilled through the literature survey. The primary reason for investigating the existing studies on AM education, AM framework and AM curriculum is to find out if there are existing studies on it and, also to find the missing gap in research and to see the need to improve the existing studies, framework and curriculum. The second objective has been fulfilled in Chapter 3 of this thesis. Section 3.2 of the Chapter 3 reviewed various papers on framework for AM technologies and it was discovered that there is no framework for AM education and the section serve as a platform or landscape for the researcher to understand how to develop a framework for AM education. Section 3.3 of the Chapter 3 investigate the recent studies on AM education and the review shows that most of the studies investigate the impact of AM on engineering education not STEM education per se. Section 3.4 investigates the recent global advancement in AM education at the universities and the review shows that some universities in the United States and Europe have included AM education into their educational system. Also, a few universities like Massachusetts Institute of Technology have developed a curriculum on AM education for engineering degree, mostly for mechanical engineering program while one or two other universities already introduced a postgraduate program in AM.

Objective 3: *To investigate the impact of AM technology and education using an empirical approach (quantitative method) for data collection among students and academics, to analyse the result and present the discussion and interpretation of the statistical analysis.*

The third objective has been met through Chapters 6 and 7. This study uses a quantitative research methodology (an empirical approach). In chapter 6, the researcher went through the proper procedure to develop a questionnaire for this study. The questionnaire includes five factors and those factors are considered associated with AM education. In chapter 7, the data was collected, analysed and the results of the analysis was discussed and interpreted appropriately by the researcher based on each factor as seen in section 7.5 of Chapter 7, including the significant insight from the open-ended questions as well.

Objective 4: *To develop a proposed framework for effective additive manufacturing education at South Africa universities.*

The fourth objective was achieved through the development of a framework for effective additive manufacturing education at the universities – a case study of South African universities as described in section 8.1 of Chapter 8. The framework was presented in Figure 8.1, the framework was divided into five important factors which would facilitate an effective AM education at the universities: AM technology, AM technology transfer, AM educational curriculum, AM in-house facilities and AM research and development (R&D). The proposed framework for AM education also includes sub-factors/characteristics that would further influence each of main factor of the framework positively towards a successful AM education implementation at the universities.

Objective 5: *To provide conclusions, contributions to knowledge and recommendations for future work.*

The fifth objective is fulfilled in chapter 9 by providing a comprehensive conclusions and recommendations. The concluding chapter further reviewed the aim, objectives and research questions in this study and confirmed that these have been fulfilled. This chapter presents the contribution to knowledge and possible future work in this research area.

The first chapter of this study shows the list of research questions formulated, these research questions were further reviewed to confirm if this study have properly answered the research questions. The research questions are expected to be answered through literature reviews, feedback and insight from the data collected and the statistical analysis from the data. The research questions consist of the main question and four sub-questions as listed and reviewed below:

The main research question:

Is there an effective framework for Additive Manufacturing education at South African universities to further promote AM education and research activities in the field?

The literature review in Chapter 3 on the recent studies on AM education and AM framework have shown that there is no existing framework for effective additive manufacturing at South Africa universities. The literature review also shows that there are limited studies tailored towards AM education at South Africa universities. Therefore, this study has answered the main research question for this study through the development of a framework for effective additive manufacturing education at South African universities as shown Figure 8.1.

Sub-research question 1:

How are the key factors/variables in the development of a framework for effective AM education derived or identified?

In any research, the key factors/variables used in the development of a framework are identified or derived through extensive literature review of previous publications. Through literature review the factors are derived or identified; and then used to develop a new framework/model or use to improve an existing framework by adding additional factors/variables. This study is not an exception of this method, the key factors/variables used in the development of a proposed framework for AM education in this study were derived through comprehensive literature survey from Chapter 2 to Chapter 5.

Sub-research question 2:

What is the perception of students and academics towards the inclusion of AM education/course in science and engineering curriculum at South Africa universities?

The question has been answered through the discussion and interpretation of the statistical analysis in Chapter 7. The results, discussion and interpretation of sub-section 3 factor on "AM Educational Curriculum" in section 7.5.3 based on the respondents' feedback to the questions in the three constructs, most especially the questions in the second construct on the "inclusion of AM education/courses into the science and engineering curriculum". The majority of the respondents' indicated 'agreed' and 'strong agreed' to these questions. More so, the respondents' feedback to first open-ended questions in section 7.7.1 clearly shows the perception of the respondents towards the inclusion of AM education to science and engineering curriculum at the South African universities as "positive" as shown in Table 7.16, that is, the summary of the key respondents' feedback to first open-ended question. The feedback of respondents to this question identifies some key benefits of inclusion of AM education such as: increase in AM awareness; increase in the number of AM professionals; enhance STEM education; allow collaboration with other fields; encourage people to pursue career in AM; improve students' engineering drawing skills; expose people to AM and promote technological advancement of AM.

Sub-research question 3:

Are there supporting factors (sub-factors) that would influence a successful inclusion or implementation of AM education at the university included in the proposed framework?

The answered to this question was met in section 8.1 of the Chapter 8. The researcher proposed a supporting factors or characteristics, which can also be referred to as sub-factors that would influence the main factors. The proposed framework for AM education was developed with the aim that each main factors/variable (i.e. AM technology, AM technology transfer, AM education curriculum, AM in-house facilities, AM research and development) cannot be standalone factor without the support of some other factors/characteristics and each of the main factor has three supporting factors/sub-factors/characteristic as shown Figure 8.1. For instance, the main factors "AM In-house facilities" requires a state-of-the-art lab to be set-up with AM facilities, AM personnel/educators is needed to train people and effective AM research group will utilize the AM facilities and conduct cutting edge research in AM.

Sub-research question 4:

What are factors necessary for sustainability of additive manufacturing technology within the educational sector and Is standardization of AM important to AM education?

This question has been answered based on literature review on the "Sustainability of Additive Manufacturing in Education Sector" as presented in chapter 5. This chapter identifies four factors suitable for sustainability of AM education, these factors are – university-industry collaboration, technology transfer, education and training, and technology and research. These factors are expected to enhance the sustainability of AM education and training at the university worldwide. For effective sustainable AM education; chapter 5 of the thesis identifies three major indices (economic, environmental and social factors) as possible indicators for sustainability of additive manufacturing.

The second question also has been answered based on the discussion on "International Standards for Sustainability of Additive Manufacturing" in section 5.5 of chapter 5. Standardization is very important to the future of additive manufacturing and also AM education and standardization is considered relevant to this study because sustainability is the key to the development of AM education and its curriculum for teaching. Understanding the importance of standardization to AM technology will assist the relevant stakeholders in STEM education to develop an appropriate strategy/framework/roadmap that will lead towards sustainability of AM education at high schools, colleges, universities and research institutions, both now and in the future. The researcher also includes a topic on "structure of AM technology standards" in the proposed AM education curriculum in section 8.1.2.2 of chapter 8 to show the importance of standardization in AM and how this topic can broaden students' perspective of AM standards.

9.2 Contributions to knowledge

This doctoral study made a number of original contributions to the current body of knowledge in the field of additive manufacturing, most significantly AM education research.

The first and most significant contribution is the development of a framework for additive manufacturing education at South African universities. The proposed framework identifies and describes the primary factors of a successful AM education framework at the university and explained how each factor work together to achieve a common goal. Moreover, this study includes sub-factors that would influence a successful AM education framework or implementation. At the time of writing this doctoral thesis, there had been very few studies focusing on AM education framework, and there are no studies on the development of a framework for AM education that uses actual data from case studies (or other research methodology) to describe or develop a framework for AM education at the universities. In this regard, this doctoral study has been able to address one of the main priorities of South Africa AM strategy which is to ensure successful adoption of AM technology in South Africa as stated in section 3.1 of Chapter 3. This study also addresses one of the essential measures identified during 2013 stakeholder meeting in South Africa which is to ensure AM education at all levels, that is, "to develop a short, medium and long-term educational framework for additive manufacturing in South Africa" as stated in section 3.1 of Chapter 3 (Du Preez *et al.*, 2016). This thesis evaluates the present and future prospects of AM education and research activities at the South Africa universities using a SWOT analysis (i.e. Strengths, weaknesses, opportunities and threats) as stated in section 3.7 of chapter 3.

This study also proposed a comprehensive sample of additive manufacturing educational curriculum which is considered suitable for teaching the fundamental AM at the South African universities both at the undergraduate or postgraduate levels as presented in sub-section 8.1.3.1 of chapter 8. This study proposed or coined the very first definition of "Additive Manufacturing Education" (AME) based on the insight gained from the various literature. This study established the importance of AM education towards the advancement of AM technology and described AM education as the key factor for AM technology to reach its full potential capacity. The study proposed that AM education should be properly integrated across different education levels. This study investigates the recent AM education and research activities across selected South Africa universities; and these universities were selected because of the strong presence of AM research group and facilities at the universities. The findings show that AM research activities at SA's universities have served as the platform for promoting AM education; this was reported in the recent paper accepted for publication by Rapid Prototyping Journal as presented in Appendix F.

This thesis clearly established that availability of "Additive Manufacturing Lab" at the universities will play a significant role in promoting AM education, empowering people with AM knowledge, enhance diver AM research activities and creates an enabling environment for advanced manufacturing technology as stated section 3.6 of chapter 3. This finding was based on the existing Idea 2 Product lab at VUT and Pukke 3D Printing Centre at NWU as described in section 3.6.1. of Chapter 2 and supported by the respondents' feedback to second open-ended question as summarized in section 7.7.2 and Table 7.17 of Chapter 7. This study provides a significant contribution or insight into the usability of "Entry-level FDM 3D printers as a tool for AM education using Idea 2 Product lab" based on its recent affordability compared to high-end industrial AM machines. This study distinctly indicated two areas where entry-level FDM 3D printers could promote AM education through the Idea 2 Product ® Lab concept: 1. Entry-Level FDM 3D Printers as a tool to Train People and; 2. Entry-Level FDM 3D Printers as a Platform for Technology Transfer. The findings is reported section 3.6.2 of Chapter 3 and as a full article/paper recently submitted for publication in Rapid Prototyping Journal as presented in Appendix G.

Conclusively, based on the empirical findings as reported in Chapter 7, this study proposed that AM education should be included in the science and engineering curriculum at South African universities. This was based on the respondents' feedback to the first open-ended question. The feedback provides very good insight as relating to the "inclusion of AM education to science and engineering curriculum at the SA universities" and the overall benefits that would come through the introduction of AM education at the South African universities were summarized in section 7.7.1. Furthermore, this study identifies the need for postgraduate programme in AM as stated in section 7.5.5.1. Therefore, this study proposed an inclusion of MSc programme in AM at selected South African universities to further strengthen the research activities in AM, ease technology transfer in AM and increase the number of AM personnel or industry professionals in AM in South Africa.

9.3 Limitations of the study and recommendations for future research

This study has provided a significant insight and adds to the state-of-the-art knowledge in AM educational framework. This study has a number of limitations and has emphasized some possible future research. One important limitation of this study is the sample size. Although this study has justified the sample size used in this study suitable and sufficient to answer the research questions. This study applied a research methodology that permit generalization of the research findings. Nevertheless, the sample size may limit the generalizations of the finding, as a result of this, the researcher suggests that future research should use large sample size for purpose of generalization.

The case study for this research was limited to selected South African universities which are within the North West and Gauteng Provinces; and this is another limitation to this study. Although, four case studies (i.e. four universities) is considered suitable for this type of study, but multiple case studies will enhance the research finding and provide better conclusion. Therefore, it is suggested that future research on AM education framework should extend the case study of the research to other South African universities with strong presence of AM in-house facilities and research group as well.

This study is limited to the development of a framework for AM education at the university, and not at the colleges or high schools and this makes the research findings suitable for university-based environment. This limitation occurs because there are little colleges or high schools in South Africa with AM in-house facilities. Future research should incorporate colleges and high schools into the development of AM education framework or AM educational curriculum implementation framework.

This study is also limited to a quantitative research methodology, where structure questionnaire was used to collect data, although the questionnaire contained two open-ended questions that allows respondents to provide useful insights and feedback that was based on their own perception. Despite this, the research findings is still very limited to a single research methodology, the researcher recommends that future work on this study could use a mixed research methodology, that is, both quantitative and qualitative research methodology to improve the research findings.

The proposed framework for additive manufacturing education in this study contained only five factors. Irrespective of any existing or developed framework, there is always a need to further improve the existing framework. The researcher believes that it is very difficult to conclude that there will be only one suitable approach to develop a framework for AM education or AM education implementation processes. Future research could enhance this framework by including some other factors considered suitable for AM education, such as (AM commercialization, AM project management and AM continuous improvement) and to provide useful insights into how the new factors can be properly integrated into the existing framework. This study does not include AM education framework implementation processes; therefore, future research should include possible implementation processes or strategies.

Conclusively, the AM education research field is still at an infant stage and requires more studies in order to realize the full potential of AM technology within the education sector, especially at this period of Fourth Industrial Revolution, FIR, (Industry 4.0). Due to the limited studies in this area of research. Therefore, the following future research is recommended:

1. A study to provide a possible approach to technology transfer that allows effective university-industry collaboration in additive manufacturing technologies and education.

2. A study to develop an educational curriculum in additive manufacturing within the South African STEM education context and describe the integration strategy.
3. A study to investigate what influences students' interest to entry-level 3D printers and later advanced to operate high-end additive manufacturing systems. The study will assist to identify those factors that influence people interest toward entry-level 3D printers and why over a period of time, he/she develop interest to work with high-end AM machines.
4. Research to investigate the impact of AM technology on the mechanical engineering degree program at selected South African universities using engineering drawing course/curriculum as the case study.
5. Research to develop a framework to integrate Industry 4.0 and additive manufacturing education using AM/3D printing laboratory concept. This type of study will provide insights into additive manufacturing education position in industry 4.0 era.

9.4 Chapter summary

This chapter concluded this study by re-visiting the research aim, objectives and research questions. This chapter has shown that the aim, objectives and research questions have been met and the study has made a significant contribution to body of knowledge AM. This chapter presented the research limitations and makes significant suggestions that would further enhance future research in this area.

References List

Abawi, K (2013). Data Collection Instruments (Questionnaire & Interview). A Training in Sexual and Reproductive Health Research Geneva workshop. http://www.gfmer.ch/SRH-Course-2012/Geneva-Workshop/pdf/Data-collection-instruments-Abawi-2013.pdf.

Akinlabi, Esther. (2016). Additive manufacturing advances in academia and teaching. A presentation at NSTF Light-based technologies innovation forum. http://www.nstf.org.za/wp-content/uploads/2016/03/Akinlabi-slides.pdf. Date of access: 11 August 2016.

Alabi. M. O. (2016). Measuring the prevailing lean culture at a South African aviation organisation. North-West University: Potchefstroom [NWU- Master].

Ali, Z. and Bhaskar, S. B. (2016). Basic statistical tools in research and data analysis. *Indian Journal of Anaesthesia*, 60(9):662–669. http://doi.org/10.4103/0019-5049.190623.

Alan Earls and Vinod Baya. (2014). The road ahead for 3-D printers. Issue 2. http://www.pwc.com/us/en/technology-forecast/2014/3d-printing/features/future-3d-printing.html. . Date of access: 09 June 2016.

AMO. (Advanced Manufacturing Office). 2012. Additive Manufacturing: Pursuing the Promise. https://www1.eere.energy.gov/manufacturing/pdfs/additive_manufacturing.pdf.

AM SRA. (2014). Additive manufacturing: Strategic Research Agenda. AM Platform – European Union Consultation Document.

AMRG (Additive Manufacturing Research Group). 2016. The 7 Categories of Additive Manufacturing. Loughborough University. http://www.lboro.ac.uk/research/amrg/about/the7categoriesofa dditivemanufacturing/. Date of access: 29 August 2016.

Anon (2016). Domain Group 3D Printing Workshop Notes. Introduction to 3D Printing. https://education.gov.mt/en/resources/News/Documents/Youth%20Guarantee/3D%20Printing.pdf. Date of access: 09 Sept. 2016.

ASTM Standard F2792-12a, Standard Terminology for Additive Manufacturing Technologies, (Withdrawn 2015), ASTM International, West Conshohocken, PA, 2012.

ASTM. (2017). Additive Manufacturing Technology Standards. https://www.astm.org/Standards/additive-manufacturing-technology-standards.html. Date of access: 28 March 2017.

ATkearney. (2015). A.T Kearney. 3D printing: a manufacturing revolution. A.T. Kearney Inc.

Azman, A.H., Vignat, F., and Villeneuve, F. (2016). Evaluating current CAD Tools Performance Context of Design for Additive Manufacturing. *Research in Interactive Design: Mechanics, Design Engineering and Advanced Manufacturing*. Vol. 4:347-355

AxisPrototypes. (2015). 3D printed samples. https://www.axisproto.com/gallery.php. Date of access: 09 Oct. 2016.

Babbie, E. R. (2010). The Practice of Social Research. 12th ed. Belmont, CA: Wadsworth Cengage.

Baker, T.L. (1994). Doing Social Research (2nd Ed.), New York: McGraw-Hill Inc.

Bak, D. (2003). Rapid prototyping or rapid production? 3D printing processes move industry toward the latter. *Assembly Automation*, *23*(4), 340-345.

Bal, M. and Abatan, A. (2017). Developing Additive Manufacturing Laboratory to Support Instruction and Research in Engineering Technology. *American Society for Engineering Education*, Paper ID #19554.

Banerjee, A., Chitnis, U. B. and Jadhav, S. L., Bhawalkar, J. S., & Chaudhury, S. (2009). Hypothesis testing, type I and type II errors. *Industrial Psychiatry Journal*, 18(2): 127–131.

Banks, J. (2013). Adding value in additive manufacturing: Researchers in the United Kingdom and Europe look to 3D printing for customization. IEEE Pulse; 4(6):22–26.

Barth, A. Caillaud, E. and Rose, B. (2011). How to Validate Research in Engineering Design? *International Conference on Engineering Design*, ICED'11. Technical University of Denmark.

Bartlett, S. (2013). Printing organs on demand. *Lancet Respir Med*, 1(9):684.

Baxter, P., & Jack, S. (2008). Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers. The Qualitative Report, 13(4):544-559, [Abstract].

Bavdekar, B. S. (2016). Formulating the Right Title for a Research Article. *Journal of the Association of Physicians of India*, Vol. 64: 53 – 56.

Bernard, H. R. 1995. Research Methods in Anthropology. Qualitative and Quantitative Approaches. Walnut Creek: Altamira Press.

Beyea, S. C and Nicoll, L. H. (1997). What is a variable? *Association of periOperative Registered Nurses Journal*, 66(3): 500-501.

Bian, H. (2017). Series 6: Exploratory Factor Analysis Hui Bian. http://core.ecu.edu/ofe/statisticsresearch/SPSS%20Series%206%20Factor%20analysis.pdf.

Blackstone, A. (2012). Field Research: A Qualitative Technique. Sociological Inquiry Principles. https://2012books.lardbucket.org/pdfs/sociological-inquiry-principles-qualitative-and-quantitative-methods.pdf. Date of access: 14 Aug. 2017.

Bland, J. and Altman, D. (1997). Statistics notes: Cronbach's alpha. BMJ, 314:275.

Borg, W. R. and Gall, M. D. (1989). Educational Research: An Introduction, 5th Ed. White Plains, New York: Longman.

Bourell, D., Leu, M. and Rosen, D. (2009). Roadmap for Additive Manufacturing—Identifying the Future of Freeform Processing. The University of Texas: Austin.

Brown, S. (2017). Measures of Shape: Skewness and Kurtosis. https://brownmath.com/stat/shape.htm. Date of access: 18 May 2018.

Brydon-Miller, M., Greenwood, D. J. and Maguire, P. (2003). Why Action Research? *Action Research*. 1(1):9-28. Sage Publications.

Bryman, A. (2007). The Research Question in Social Research: What is its Role? *International Journal of Social Research Methodology*, Vol.*10: 5-20.*

BuildProtos. (2017). 3D Printing in Research and Development. http://buildprotos.com/3d-printing-in-research/. Date of access: 24 September 2018.

Bull, G., Maddox, C., Marks, G., McAnear, A., Schmidt, D.' Schrum, L. (2010). Educational implications of the Digital Fabrication Revolution. *Journal of Research on Technology in Education*, 42(4).8.

Burmeister, E and Aitken, L. M. (2012). Sample size: How many is enough? *Australian Critical Care Journal*, pp1-10. https://doi.org/10.1016/j.aucc.2012.07.002.

Campbell, R.I., & De Beer, D.J. (2005). Rapid prototyping in South Africa: past, present and future. *Rapid Prototyping Journal.* 11(4): 260 – 265.

Campbell, R.I., De Beer, D.J. & Pei, E. (2011). Additive manufacturing in South Africa: building on the foundations. *Rapid Prototyping Journal.* 17(2):156 – 162.

Campbell, R. I. and De Beer, D. J. (2017). Using-Idea 2-Product Labs as a Strategy for Accelerating Technology Transfer. International Journal of Technology Transfer and Commercialisation, 14(2): 249-261.

Carpiano, R. M. and Daley, D. M. (2006). A guide and glossary on postpositivist theory building for population health. *Journal of Epidemiol Community Health*. Vol. 60, pp564–70.

Cummings, I. T., Bax, M. E., Fuller, I. J., Wachtor, A. J. and Bernardin, J. D. (2017). A Framework for Additive Manufacturing Process Monitoring & Control. Topics in Modal Analysis and testing, Vol. 10. Publisher: Springer.

Charmaz, K. (2003). Grounded Theory - The SAGE Encyclopedia of Social Science Research Methods**.** SAGE Publications 2009.

Chausovsky, Alex. (2014). The Impact of 3D Printing on Industrial Manufacturing. IHS Technology.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., GarðarSteingrímsson, J. and Thiede, S. (2015). Direct digital manufacturing: definition, evolution, and sustainability implications. J. Cleaner Prod. 107:615–625.

Chua, K. J., Yang, W. M., and Leo, H. L. (2014). Enhanced and conventional project-based learning in an engineering design module. *International Journal of Technology and Design Education*, 24(4): 437- 458. http://dx.doi.org/10.1007/s10798-013-9255-7.

Chua, K. C., Leong, K.F. and Liu, Z.H. (2014). Rapid Tooling in Manufacturing. Handbook of Manufacturing Engineering and Technology, pp1-22. London: Springer. [Abstract].

Chung, Chris. (2014). Five key issues preventing Additive Manufacturing from reaching its potential. http://blog.lr.org/2014/11/five-key-issues-preventing-additive-manufacturing-from-reaching-its-potential/. Date of access: 04 July 2016.

Cohen, R. J. and Swerdlik, M. E. (2005) Psychological Testing and Assessment, 6th Edition. New York: McGraw Hill.

Colletti, R. C. (2016). A study of positions available in additive manufacturing/3D printing and the education and skill requirements for these positions. Michigan: Eastern Michigan University [EMU: Doctoral Thesis]. http://commons.emich.edu/theses/688/.

Cotteleer, M., Holdowsky, J. and Mahto, M. (2014). The 3D opportunity primer: the basics of additive manufacturing. http://dupress.com/articles/the-3d-opportunity-primer-the-basics-of-additive-manufacturing/. Date of access: 22 August 2016.

Cotteleer, M., Crane, J. and Neier. M. (2014). 3D opportunity in tooling Additive manufacturing shapes the future. https://dupress.deloitte.com/content/dam/dup-us-en/articles/additive-manufacturing-3d-opportunity-in-tooling/3D-opportunity-in-tooling1.pdf. Date of access: 26 Oct. 2016.

Cramer, D and Dennis, H. (2004). The SAGE Dictionary of Statistics. London: SAGE.

Crawford, I. M. (1997). Chapter 4: Questionnaire Design. Marketing Research and Information Systems. (Marketing and Agribusiness Texts - 4). Food and Agricultural Organization of United State. http://www.fao.org/docrep/w3241e/w3241e05.htm. Date of access: 17 Aug. 2017.

Creswell, J. W. (1994). Research Design: Qualitative and Quantitative Approaches. Thousand Oaks. CA: Sage Publication.

Creswell, John. W. (2014). Research design: qualitative, quantitative and mixed methods approaches. 4th ed. Los Angeles: Sage Publication.

Cronbach, L. (1951). Coefficient alpha and the internal structure of tests. Psychomerika. Vol. 16: pp297-334.

CSC. (2012). 3D Printing and the Future of Manufacturing. assets1.csc.com/innovation/downloads/LEF_20123DPrinting.pdf. Date of access: 09 June 2016.

CTI Review. (2016). Educational Research, Planning, Conducting, and Evaluating Quantitative and Qualitative Research: Statistics, Statistics. Cram101 Textbook Reviews. 4th Ed.

Cui, X., Boland, T., D'Lima, D. D and Lotz, M. K. (2012). Thermal inkjet printing in tissue engineering and regenerative medicine. *Recent Pat Drug Deliv Formul*, 6(2):149–155.

CustomPartNet (2009). Direct Metal Laser Sintering. http://www.custompartnet.com/wu/direct-metal-laser-sintering. Date of access: 12 Sept. 2016.

De Beer, D. J. (2010). Additive manufacturing as tool to support sustainable development. *Annals of DAAAM for 2010 & Proceedings for the 21st International DAAAM symposium. Academic Journal.* 21(1).

De Beer, D.J. (2011). Establishment of rapid prototyping/additive manufacturing in South Africa. *Journal of the South African Institute of Mining and Metallurgy,* 111(3):211-215.

De Beer, D. J., and Du Preez, W.B. (2015). Implementing the South Africa additive manufacturing technology roadmap – The role of an Additive Manufacturing Centre of Competence. *South African Journal of Industrial Engineering*, 26(2):85-92.

De Beer, D, J. (2015b). South African Additive Manufacturing Landscape/Growth of 3D Printers, 1991-2015. [The diagram in Figure 1.1 was supplied by Deon De Beer in 2015].

De Beer, D.J. (2016). Thinking in layers: Talk on additive manufacturing. NSTF Awards in partnership with South32 at NMMU. Share 'n Dare outreach programme.

Delice, A. (2010). The Sampling Issues in Quantitative Research. *Educational Sciences: Theory & Practice*, 10(4): 2001-2018. https://files.eric.ed.gov/fulltext/EJ919871.pdf.

DeVellis, R. (2003). Scale development: theory and applications: theory and application. Thousand Oaks, CA: Sage publication.

Dickens, P., Reeves, P. and Hague, R. (2016). Additive Manufacturing Education in the UK. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-01-Dickens.pdf.

Diegel, Olaf., Singamneni, Sarat., Reay, Stephen., and Withell, Andrew. (2010). Tools for Sustainable Product Design: Additive Manufacturing. *Journal of Sustainable Development.* 3(3):68-75.

Deradjat, D. and Minshall, T. (2015). Implementation of additive manufacturing technologies for mass customisation. *Proceedings of International Association for Management of Technology IAMOT 2015 Conference*, pp2079-2094.

Deradjat, D. and Minshall, T. (2017) "Implementation of rapid manufacturing for mass customisation", Journal of Manufacturing Technology Management, Vol. 28 Issue: 1, pp.95-121, https://doi.org/10.1108/JMTM-01-2016-0007

Despeisse, M. Ford, S. and Viljakainen, A. (2015). Product life extension through additive manufacturing: The business model implications. Working Paper. DOI: 10.13140/RG.2.1.4561.9282.

Despeisse, M. and Minshall, T. H. (2017). Skills and Education for Additive Manufacturing: A Review of Emerging Issues. APMS 2017: Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, 513: 289-297.

Dimitrov, D., Schreve, K., & De Beer, N. (2006). Advances in Three Dimensional Printing - State of the Art and Future Perspectives. *Rapid Prototyping Journal*, 12(3), 136-147.

Dimitrov, D. (2006), "Stellenbosch University, Department of Industrial Engineering proves the value of 3D printing in manufacturing, architecture, and education", 3d Rapid Prototyping Case Studies: Stellenbosch University. http://www.3dsystems.com/learning-center/case-studies/stellenbosch-university-department-industrial-engineering-proves-value. Date of access: 01 July 2016.

Dimitrov, D.M. & De Beer, N. (2014). Improvements in the capability profile of 3-D printing: An update. *South African Journal of Industrial Engineering.*25 (2): 1-12.

Donaldson, B. (2018). Auburn University offers a Certificate in Additive Manufacturing. https://www.additivemanufacturing.media/articles/auburn-universitys-roadmap-to-additive-manufacturing-education. Date of access: 11 June 2018.

Drakoulaki, A. (2017). 3D printing as Learning Activity in Higher Education: A case study in a robotics' prototyping course. Oslo: University of Oslo. [UiO: Master – Dissertation].

Du Plessis, S. (2015). Is working with 3D printers a dangerous occupation? http://mg.co.za/article/2015-07-30-is-working-with-3d-printers-a-dangerous-occupation. Date of access: 01 July 2016.

Du Preez, W. B and de Beer, D. J. (2006). RAPDASA–A vehicle for product development technology diffusion in South Africa. Doc No: CSIR/MSM/MMP/EXP/2006/0082/A.

Du Preez, W., De Beer, D., Greyling, H., Prinsloo, F., Sciammarella, F., Trollip, N., Vermeulen, M. and Wohlers, T. (2016). A South African Additive Manufacturing Strategy. Department of Science and Technology.

Dudovskiy, J. (2016). The Ultimate Guide to Writing a Dissertation in Business Studies: A Step-by-Step Assistance. http://research-methodology.net/research-methodology/research-design/exploratory-research/. Date of access: 10 Aug. 2017.

Eugene, M. and Lynn, C.E. (2017). Research Methods in the Social Sciences- Exploratory Design. Lynn University Library. lynn-library.libguides.com/c.php?g=549455&p=3771805. Date of access: 10 Aug. 2017.

EOS. (2013). Additive Manufacturing in Dentistry. https://scrivito-public-cdn.s3-eu-west-1.amazonaws.com/eos/public/508ff2c0a6165bd3/592e0bee1b66556f3f774fd579c4c628/dentalbroschuere.pdf. Date of access: 16 Oct 2016.

EOS (2016). Additive Manufacturing, Laser-Sintering and industrial 3D printing - Benefits and Functional Principle. http://www.eos.info/additive_manufacturing/for_technology_interested. Date of access: 12 Sept. 2016.

Ethridge, D. E. (2004). *Research Methodology in Applied Economics,* 2nd ed. Wiley-Blackwell., pp24.

European Commission. (2014). Additive Manufacturing in FP7 and horizon 2020. Report from the EC workshop on additive manufacturing.

Faludi, J., Hu, Z., Alrashed, S., Braunholz, C., Kaul, S. and Kassaye, L. (2015). Does Material Choice Drive Sustainability of 3D Printing? *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering,* World Academy of Science, Engineering and Technology, 9(2):144-151.

Ferchow, J., Klahn, C. and Meboldt, M. (2018). Enabling Graduate Students to Design for Additive Manufacturing through Teaching and Experience Transfer. *International Conference on Engineering and Product Design Education.* pp. 1-6.

Ferroa, C., Grassia, R., Seclìb, C., and Maggiorea, P. (2016). Additive Manufacturing Offers New Opportunities in UAV Research. *48th CIRP Conference on Manufacturing Systems - CIRP CMS 2015.* Procedia CIRP 41:1004 – 1010.

Fisher, M. L. (1997). What is the right supply chain for your product? *Harvard business review, 75*, 105-117.

Ford, S. L. (2014). Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness. *Journal of International Commerce and Economics*. http://www.usitc.gov/journals.

Ford, S., Viljakainen, A., and Despeisse, M. (2015). Extending product life through additive manufacturing: The sustainability implications. Conference Paper: Global Conference on Cleaner Production and Sustainable Consumption, At Sitges, Spain.

Ford, S. and Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production,* 137 (2016) 1573 -1587.

Fox, N., Hunn, A. and Mathers, N. (2009). Sampling and sample size calculation The NIHR RDS for the East Midlands / Yorkshire & the Humber.

Frankfort-Nachmias, C and Nachmias, D. (1996). Research Methods in the Social Sciences. London: Arnold.

Fratila, D. and Rotaru, H. (2017). Additive manufacturing – a sustainable manufacturing route. MATEC Web of Conferences, Vol. 94, 03004.pp1-13. DOI: 10.1051/matecconf/20179403004.

Frost & Sullivan, 2007. World Rapid Prototyping Equipment Markets. http://www.researchandmarkets.com/reports/480632/world_rapid_prototyping_equipment_markets. Date of access: 11 Oct. 2016.

Frost, J. (2018a). Difference between Descriptive and Inferential Statistics. http://statisticsbyjim.com/basics/descriptive-inferential-statistics/. Date of access: 25 August 2018.

Frost, J. (2018b). Measures of Variability: Range, Interquartile Range, Variance, and Standard Deviation. http://statisticsbyjim.com/basics/variability-range-interquartile-variance-standard-deviation/

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S., and Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design* .69:65–89.

GAO (United States Government Accountability Office). 2015. Opportunities, Challenges, and Policy: Implications of Additive Manufacturing. Highlights of a forum Convened by the Comptroller General of the United States.

Gatto, A. Bassoli, E., Denti, L., Luliano, L. and Minetola, P. (2015). Multi-disciplinary approach in engineering education: learning with additive manufacturing and reverse engineering, Rapid Prototyping Journal, 21(5): 598-603.

Gausemeier, J., Echterhoff, N., Kokoschka, M and Wall, M. (2011). Thinking Ahead, the Future of Additive Manufacturing - Analysis of Promising Industries. Direct Manufacturing Research Centre. Heinz Nixdorf Institute. University of Paderborn.

Gausemeier, J., Echterhoff, N. and Wall, M. (2013). Thinking ahead the Future of Additive Manufacturing – Innovation Roadmapping of Required Advancements. Heinz Nixdorf Institute, University of Paderborn.

Gilpin, L. (2014). 10 industries 3D printing will disrupt or decimate. http://www.techrepublic.com/article/10-industries-3d-printing-will-disrupt-or-decimate/. Date of access: 30 June 2016.

Gibson, I., Rosen, D. W and Stuker, B. (2010) Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. p.34. New York: Springer-Verlag.

Glass, G.V. and Hopkins, K. D. (1984). Statistical Methods in Education and Psychology, Englewood Cliffs, New Jersey: Prentice Hall.

Go, J. and Hart, A. J. (2016). A framework for teaching the fundamental of additive manufacturing and enabling rapid innovation. *Additive Manufacturing Journal*, Elsevier, Vol. 10: 76-87. http://dx.doi.org/10.1016/j.addma.2016.03.001.

Gravetter, F. J. and Wallnau, LB. (2000). Statistics for the behavioural sciences. 5th ed. Belmont: Wadsworth – Thomson Learning.

Gross, B. C, Erkal, J. L., Lockwood, S.Y., Chen, C and Spence, D.M. (2014). Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. *Anal Chem,* 86(7):3240–3253.

Grünberger, T and Domröse, R. (2015). Direct Metal Laser Sintering: Identification of process phenomena by optical in-process monitoring. *Laser Technik Journal.* 1: 45-48

Grynol, B. (2013). Disruptive manufacturing: the effects of 3D printing. Innovative thinking: inside out. Toronto, Ontario: Deloitte.

Gunasekaran, A. and Spalanzani, A. (2012). Sustainability of manufacturing and services: Investigations for research and applications. *International Journal of Production Economics*, 140(1): 35-47. http://dx.doi. org/10.1016/j.ijpe.2011.05.011.

Guo, N., and Leu, M. C. (2013). Additive Manufacturing: Technology, Applications and Research Needs. *Frontiers of Mechanical Engineering*, 8(3): 215-243.

Hague, R., Reeve, P. and Jones, S. (2016). Additive manufacturing: mapping UK research into 3D printing. https://www.gov.uk/government/publications/additive-manufacturing-mapping-uk-research-into-3d-printing. Date of access: 02 May 2017.

Hao, L., Raymond, D., Strano, G and Dadbakhsh, S (2010). Enhancing the sustainability of additive manufacturing. *5th International Conference on Responsive Manufacturing - Green Manufacturing (ICRM 2010),* pp. 390-395.

Handal, R. (2017). An Implementation Framework for Additive Manufacturing in Supply Chains. Journal of Operations and Supply Chain Management, 10(2):18-31

Harris, S. (2011). Additive Manufacturing: Looking the part. The Engineer. p38.

Harmon, R.J and Morgan, G.A. (1999). Research problems and variables. *Journal of the American Academy of Child and Adolescent Psychiatry*, Vol. 38:784-786.

Harvey, S. (2016). Teaching Additive Manufacturing in a Higher Education Setting. *Proceeding of Australia Association for Engineering Education, AAEE 2016.* Coffs Harbour, Australia, pp1-8.

Hassan, A. Z., Schattner, P. and Mazza, D. (2006). Doing a pilot study: Why is it essential? *Malaysian Family Physician*, 1(2&3):70-73.

Hatcher, L. (1994). A step-by-step approach to using the SAS(R) system for factor analysis and structural equation modelling. Cary, NC: SAS Institute.

Havenga, S. (2017). Entry Level 3D Printing – Idea 2 Product Lab. Information Supplied by Sarel Havenga, Technology Transfer and Innovation, I2P Lab VUT Science and Technology Park, Sebokeng Campus.
Hiemenz, J. (2007). Electron Beam Melting. Advanced Materials & Processes.

Hill, R. (1998). What sample size is "enough" in internet survey research? Interpersonal Computing and Technology: An Electronic Journal for the 21st Century, 6(3-4).

Hill, T., Lewicki, P. and Lewicki, P. (2006). Statistics: Methods and Applications: a Comprehensive Reference for Science, Industry, and Data Mining. StatSoft Inc. Publisher.

Hogan, J., Dolan, P., Donnelly, P. (2009). Introduction: Approaches to Qualitative Research: Theory and Its Practical Application, pp. 1-18. Cork: Oak Tree Press.

Holtrup, R. (2015) XZEED DLP. A multi-material 3D printer using DLP technology. Enschede, Netherlands: University of Twente (Dissertation - Bachelor).

HousingObserver. (2015). 3D Printing and the Construction Industry. Canada Mortgage and Housing Corporation.

Huang, S. H., Liu, P., Mokasdar, A. and Hou, L. (2013). Additive manufacturing and its societal impact: a literature review, *International Journal of advanced manufacturing technology*, 67(5-7): 1191-1203.

Huang, Y. and Leu, M. C. (2014). Frontiers of Additive Manufacturing Research and Education. Center for Manufacturing Innovation. Florida: University of Florida.

Huang, Y, Leu, M. C, Mazumder, J. and Donmez, A. (2015). Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. *Journal of Manufacturing Science and Engineering.* Vol. 137: 014001-014010.

Hague, R., Reeve, P. and Jones, S. (2016). Additive manufacturing: mapping UK research into 3D printing. https://www.gov.uk/government/publications/additive-manufacturing-mapping-uk-research-into-3d-printing. Date of access: 01 Dec. 2017.

Huston, D., Van Epps, A., Sherrill, J., Alvar, A. and Bowen, A. (2015). How 3D Printers Support Teaching in Engineering, Technology and Beyond. https://www.asist.org/publications/bulletin/oct-15/how-3d-printers-support-teaching/. Date of access: 24 March 2017.

IDRE. (2017). What does Cronbach's alpha mean? – SPSS FQA. Institute for Digital Research and Education. https://stats.idre.ucla.edu/spss/faq/what-does-cronbachs-alpha-mean/. Date of access: 19 Aug. 2017.

Isaac, S., & Michael, W. B. (1995). Handbook in research and evaluation. San Diego, CA: Educational and Industrial Testing Services.

Isaac, S. and Micheal, W. S. (1997). Handbook in research and evaluation: A collection of principles, methods, and strategies useful in the planning, design, and evaluation of studies in education and the behavioural sciences. San Diego: Educational and Industrial Testing Services.

Ishengoma, F. R. & Mtaho, A. B. (2014). 3D Printing: developing countries perspectives. *International Journal of Computer Applications.* 104(11):30-34.

Jasveer, S. and Xue Jianbin, X. (2018). Comparison of Different Types of 3D Printing Technologies. *International Journal of Scientific and Research Publications,* 8(4): 1 – 9. http://www.ijsrp.org/research-paper-0418/ijsrp-p7602.pdf.

Jing, S., Song, G., Liu, J., Zhou, J. and Zhang, H. (2014). A Review of Product Design for Additive Manufacturing. *Applied Mechanics & Materials.* 635-637: p97.

Jordaan, G. D. 2010. A Business Model for Rapid Prototyping in South Africa. *Academic Journal.* Annals of DAAAM & Proceedings; 2010, p1561. http://www.freepatentsonline.com/article/Annals-DAAAM-Proceedings/246014346.html.

Jürgen, G., Marina, W. & Stefan, P. 2013. Thinking ahead the Future of Additive Manufacturing - Exploring the Research Landscape. Heinz Nixdorf Institute, University of Paderborn.

Kai, D.A., Lima, E.P., Cunico, M.W.M. and Gouvea da Costa. S.E. (2016). Measure Additive Manufacturing for Sustainable Manufacturing. Conference paper: Conference: 2016 ISPE International Conference on Transdisciplinary Engineering, At Curitiba, Vol.4. DOI: 10.3233/978-1-61499-703-0-186.

Kallet, R. H. (2004). How to Write the Methods Section of a Research Paper. Respiratory Care 49(10), pp1229-1232.

Karsten, J and West, D. 2015. Additive manufacturing builds concerns layer by layer. http://www.brookings.edu/blogs/techtank/posts/2015/12/08-additive-manufacturing-builds-concerns. Date of access: 24 June 2016.

Kellens, K., Renaldi, R., Dewulf, W., Kruth, J. and Duflou, J. R. (2014). Rapid Prototyping J 20, pp: 459–470.

Kianian, B., Tavassoli, S., Larsson, T. C., and Diegel, O. 2016. The Adoption of Additive Manufacturing Technology in Sweden. *13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use*. Procedia CIRP 40: p7 – 12.

Kirk, R. E. (1995). Experimental design: procedures for the behavioral sciences, 3rd ed. Monterey: Cole Publishing.

Klein, G.T., Lu, Y. and Wang, M.Y. (2013). 3D printing and neurosurgery—ready for prime time? *World Neurosurg*, 80(3/4):233–235.

Klöden, B. (2016). Additive Manufacturing: Electron Beam Melting. Fraunhofer Institute for Manufacturing Technology and Advanced Materials, IFAM.

Knupfer, N. N. and McLellan, H. (1996). 4.1 Descriptive research methodology. Handbook of research methodologies in educational communication technology. Pp 1196-1212.

Kochan, A. (2000). Rapid prototyping gains speed, volume and precision. *Assembly Automation*, 20(4):295.

Kroll, E., & Artzi, D. (2011). Enhancing Aerospace Engineering Students' Learning with 3D Printing Wind-Tunnel Models. *Rapid Prototyping Journal*. 17(5): 393-402.

Kuhn, Carol. 2013. Additive Manufacturing in 3D product design and development practice: an interdisciplinary shift. (2013 Design Education Forum of Southern Africa (DEFSA) *conference proceedings*, VUT, South Africa. P.145-153).

Kulkarni, S. (2013). 3 Basic tips on writing a good research paper title. https://www.editage.com/insights/3-basic-tips-on-writing-a-good-research-paper-title. Date of access: 15 Aug. 2017.

Kunniger, Daniel. 2015. Diffusion of additive manufacturing in Gauteng South Africa. Pretoria: University of Pretoria. (Dissertation – Masters).

Lancaster, G. A., Dodd, S. and Williamson, P. R. (2004). Design and analysis of pilot studies: recommendations for good practice. *J Eval Clin Pract*, 10(2):307-12.

Lane, D. M. (2013). Measures of Variability. http://onlinestatbook.com/2/summarizing_distributions/variability.html. Date of access: 25 August 2018.

Le Bourhis, F., Kerbrat, O., Hascoet, J., Mognol, P. (2013). Internal Journal of Advanced Manufacturing Technology. 69:1927–1939.

Le Bourhis, F., Kerbrat, O., Dembinski, L., Hascoet, J. and Mognol, P. (2014) Procedia CIRP 15, 26–31.

Leedy, P.D. & Ormrod, J.E. 2010. Practical research (9th ed.). New Jersey: Merrill Pearson.

Lenth, R. V. (2001). Some Practical Guidelines for Effective Sample Size Determination. *The American Statistician*, 55, 3, pp. 187-193.

Lenz, J. (2015). Standardization of industrial additive manufacturing. A presentation at the International Conference on Additive Manufacturing.

Leroy, G. (2011). Chapter 2- Variables. Designing User Studies in Informatics, Health Informatics, pp29-53. Springer: London. DOI 10.1007/978-0-85729-622-1_2.

Li, J., Myant, C. and Wu, B. (2016). The current landscape for additive manufacturing research: A review to map the UK's research activities in AM internationally and nationally. Imperial College Additive Manufacturing Network.

Lim, S., Buswell, R. A., Le, T.T., Austin, S.A., Gibb, A.G.F. and Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction,* 21 (1):262-268.

Lin, F., Zhang, L., Zhang, R. and Zhang, T. (2012). Innovative education in additive manufacturing in China. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-02-Lin.pdf.

Lloyd's Register. (2016). The opportunities for Additive Manufacturing in the Energy Industry. Lloyd's Register Energy.

López, Elliot, Nieves, Hilca., Abad, Clara, and Ortiz, Jorge. R. 2010. Some Reflections on "Data Interpretation and Discussion". http://ecoplexity.org/?q=reflection_data. Date of access: 07 July 2016.

Lu, Bingheng., Li, Dichen and Tian, Xiaoyong. (2015). Development trends in additive manufacturing and3 D printing. *Engineering Sciences Press.* 1(1):085-089.

Liu, Z., Jiang, Q., Zhang, Y. and Zhang, H. (2016). Sustainability of 3D Printing: A critical review and recommendations. ASME. International Manufacturing Science and Engineering Conference. Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing, Vol. 2. [Abstract].

Makerstation. (2017). Idea to Product plus Lab. http://makerstation.co.za/i2plab/. Date of access: 17 January 2018.

Malshe, H., Nagarajan, H., Pan., Y. and Haapala, K. (2015). Profile of sustainability in additive manufacturing and environmental assessment of a novel stereolithography process. ASME. International manufacturing science and engineering conference. Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing, Vol. 2.

Mançanares, C. G., Zancul, E. and Cauchick-Miguel, P. A. (2015). Sustainable manufacturing strategies: a literature review on additive manufacturing approach. Product: Management & Development, 13(1):47-56. http://dx.doi.org/10.4322/pmd.2015.001.

Manikandan, S. (2011). Measures of central tendency: The mean. *Journal of Pharmacology & Pharmacotherapeutics*, *2*(2), 140–142. http://doi.org/10.4103/0976-500X.81920.

Maree, K (ed.). 2007. *First steps in research*. Pretoria: Van Schaik.

Mark, C., & Jim, J. 2014. 3D opportunity: Additive manufacturing paths to performance, innovation, and growth. Deloitte Review issue 14. http://dupress.com/articles/dr14-3d-opportunity/. Date of access: 09 June 2016.

Mark, C., Mark, N. & Jeff, C. 2014. 3D opportunity in tooling additive manufacturing shapes the future. http://dupress.com/articles/additive-manufacturing-3d-opportunity-in-tooling/. Date of access: 09 June 2016.

Martin, A. (2013). Exciting Developments in Uses of 3D Printing in Education. http://www.emergingedtech.com/2013/05/exciting-developments-in-uses-of-3d-printing-in-education/. Date of access: 08 Nov. 2016.

Martz, E. (2013). Bewildering Things Statistician Say: Failure to Reject the Null Hypothesis". http://blog.minitab.com/blog/understanding-statistics/things-statisticians-say-failure-to-reject-the-null-hypothesis. Date of access: 12 September 2018.

Mathers, N., Fox, N. and Hunn, A. (2007). Surveys and Questionnaires. *National Institute for Health Research*. The NIHR RDS for the East Midlands / Yorkshire & the Humber.

McKinney, G. (2017). Qualitative Research: Grounded Theory: What is it? Temple University Library. http://guides.temple.edu/groundedtheory. Date of access: 11 Aug. 2017.

Mellor, S. Hao, L. and Zhang, D. (2013) Additive Manufacturing: A framework for implementation. *International Journal of Production Economics,* 149:194-201. http://dx.doi.org/10.1016/j.ijpe.2013.07.008.

Mellor, S. (2014). An Implementation Framework for Additive Manufacturing. Exeter: University of Exeter. [UoE: PhD Thesis].

Menezes, Reuben. (2013). The Impact of Additive Manufacturing on Society: A detailed look into the influences of 3D engineering on manufacturing and innovation. http://proto3000.com/news/2013/05/13/3dprinting/impact-of-additive-manufacturing. Date of access: 26 August 2016.

Mertz, L. (2013). Dream it, design it, print it in 3-D: What can 3-D printing do for you? *IEEE Pulse,* 4(6):15–21.

Miller, L. A., Lovler, R.L. and McIntire, S. A. (2012). Foundation of Psychological Testing: A Practical Approach. California, SAGE Publications.

Minetola, P., Luliano, L., Bassoli, E. and Gatto, A. (2015). Impact of additive manufacturing on engineering education - evidence from Italy. *Rapid Prototyping Journal, Emerald Group Publishing Ltd*., 25(5):535-555.

Minshall, T. and Dickens, P. (2015). How was the evidence collected? UK National Strategy for Additive Manufacturing. http://www.amnationalstrategy.uk/wp-content/uploads/2015/05/UK-AM-National-Strategy-Update-Report-1.2.pdf. Date of access: 11 June 2018.

MIT (Massachusetts Institute of Technology). 2016. Additive Manufacturing: From 3D Printing to the Factory Floor. http://professional.mit.edu/programs/short-programs/additive-manufacturing. Date of access: 27 June 2016.

Mpofu, T. P., Mawere, C., and Mukosera, M. 2014. The Impact and Application of 3D Printing Technology. *International Journal of Science and Research (IJSR),* 3(6): 2148- 2152.

Molitch-Hou, M. (2015). House 3D Printing Fortified with WASP's Reinforced Concrete Beams. http://3dprintingindustry.com/news/house-3d-printing-fortified-with-wasps-reinforced-concrete-beams-55345/. Date of access: 07 Nov. 2016.

Muijs, D. (2010). Doing Quantitative Research in Education with SPSS. 2nd ed. London: SAGE Publications.

Munoz, C., Kim, C. and Armstrong, L. (2013). Layer-by-Layer: Opportunities in 3D printing Technology trends, growth drivers and the emergence of innovative applications in 3D printing. MaRS Market Insight Discovery

Muthu, S. S. and Savalani, M. M. (2016). Handbook of Sustainability in Additive Manufacturing, Environmental Footprints and Eco-design of Products and Processes. Singapore: Springer [Abstract]. DOI 10.1007/978-981-10-0549-7_2.

Naden, C. (2016). ISO and ASTM International unveil framework for creating global additive manufacturing standards. https://www.iso.org/news/2016/10/Ref2124.html. Date of access: 28 March 2017.

Nilsen, P. (2015). Making sense of implementation theories, models and frameworks. *Journal of Implementation Science,* 10(53):1-13. http://doi.org/10.1186/s13012-015-0242-0.

NIST (National Institute of Standards and Technology) 2013. Measurement Science Roadmap for Metal-Based Additive Manufacturing, Gaithersburg, MD.

Noorani, R. (2006). Rapid Prototyping – Principles and Applications, John Wiley & Sons.

Nunnally, J. and Bernstein, L. (1994). Psychometric theory. New York: McGraw-Hill Higher, INC;

Nunnally, J. C. and Bernstein, I. H. (1994). The Assessment of Reliability. Psychometric Theory, 3, 248-292.

Nyrhila, olli., Danzig, Andre and Frey, Michae. (2010). Direct Metal Laser Sintering (DMLS) of Alloys. Orlando, FL, USA. [Abstract].

O’Brien, R. (2001). An Overview of the Methodological Approach of Action Research. http://www.web.ca/~robrien/papers/arfinal.html. Date of access: 14 Aug. 2017.

Olson, R. (2013). The Environmental Forum: 3D Printing: A boon or a bane? Advancing environmental protection through analysis, opinion and debate. *The Policy Journal of the Environmental Law Institut*e, 30(6):33-38.

Ommani, A. R. (2011). Strengths, weaknesses, opportunities and threats (SWOT) analysis for farming system businesses management: Case of wheat farmers of Shadervan District, Shoushtar Township, Iran. *African Journal of Business Management*, 5(22): 9448-9454.

Optimizely. (2017). Statistical Significance. https://www.optimizely.com/optimization-glossary/statistical-significance/. Date of access: 29 Aug. 2017.

Ozbolat, I. T and Yu, Y. (2013). Bioprinting toward organ fabrication: challenges and future trends. *IEEE Trans Biomed Eng*, 60(3):691–699.

Pallant, J. (2011). SPSS Survival Manual: a step by step guide to data analysis using SPSS. 4th edition. Australia: Allen & Unwin.

Panesar, A., Brackett, D., Ashcroft, I., Wildman, R. and Hague, R. (2015). Design Framework for Multifunctional Additive Manufacturing: Placement and Routing of Three-Dimensional Printed Circuit Volumes. *Journal of Mechanical Design*, 137(11).

Patino, C. M. and Ferreira, J. C. (2015). Confidence intervals: a useful statistical tool to estimate effect sizes in the real world. Jornal Brasileiro de Pneumologia, 41(6):565-566.

Peña, V., Lal, B. and Micali, M. (2015). National Science Foundation's Role in Additive Manufacturing. IDA Research Note.pp59 – 60.

Penslar, R. L. and Joan, P. P. (2010). Institutional Review Board Guidebook: Introduction. Washington, DC: United States Department of Health and Human Services, 2010; "What are Dependent and Independent Variables?".

Perkel, J. M. (2015). Biomedical Applications of 3D Printing. http://www.biocompare.com/Editorial-Articles/178792-Biomedical-Applications-of-3D-Printing/. Date of access: 27 Oct. 2016.

Piedmont, R. L. (2014). Inter-item Correlations. Encyclopedia of Quality of Life and Well-Being Research, pp 3303-3304. Springer: Netherlands. DOI:10.1007/978-94-007-0753-5_1493

Pieterse, F.F. & Nel, A.L. 2016. The advantages of 3D printing in undergraduate Mechanical Engineering research. (2016 IEEE Global Engineering Education Conference (EDUCON). Abu Dhabi, UAE. P. 25-31).

Platt, J. R. (2015). Thirty-five percent of engineering jobs now require 3-D printing skills. http://theinstitute.ieee.org/career-and-education/career-guidance/thirtyfive-percent-of-engineering-jobs-now-require-3d-printing-skills. Date of access: 24 March 2017.

Polit, D.F., Beck, C.T. and Hungler, B.P. 2001. Essentials of Nursing Research: Methods, Appraisal and Utilization. 5th Ed., Philadelphia: Lippincott Williams & Wilkins.

Pradel, P., Zhu, Z., Bibb, R. and Moultrie, J. (2018): A framework for mapping design for additive manufacturing knowledge for industrial and product design, *Journal of Engineering Design*, pp1-37. DOI: 10.1080/09544828.2018.1483011.

Prasad, S., Rao, A. and Rehani, E. (2001). Developing hypothesis and research questions. 500 research methods.

QTR (Quadrennial Technology Review). 2015. Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. Additive Manufacturing Technology Assessment. US Department of Energy.

Radharamanan, R. (2017). Additive Manufacturing in Manufacturing Education: New Course Development and Implementation. *American Society for Engineering Education, ASEE Annual Conference and Exposition paper*. Pp 1-14. Paper ID #20377.

Reason, P and Bradbury, H. (2001). Handbook of action research: Participative inquiry and practice. London: Sage Publications.

RAE (Royal Academy of Engineering). 2013. Additive Manufacturing: opportunities and constraints. A summary of a roundtable forum. London: Prince Philip House.

Reeves, S. and Kuper, A. (2008). Qualitative research methodologies: ethnography. http://www.bmj.com/content/337/bmj.a1020. Date of access: 11 Aug. 2017.

Rehman, A. (2014). Save the Environment with Additive Manufacturing. http://3dprinthq.com/save-the-environment-with-additive-manufacturing/. Date of access: 13 Nov. 2016.

Reyes-García, V. and Sunderlin, W. D. (2011). Chapter 2. Why Do Field Research. Center for International Forestry Research (CIFOR). Pp17-32.

Reynaldo, J and Santos, A. (1999). Cronbach's Alpha: A Tool for Assessing the Reliability of Scales. *Journal of extension*, 37(2).

Roitenberg, J. (2016). The Intersection of STEM and 3D Printing in Higher Ed. http://eschoolmedia.com/wp-content/uploads/2016/06/StratasysPOV1208.pdf. Date of access: 18 Sept. 2018.

Rosen, W. David. (2007) Computer-Aided Design for Additive Manufacturing of Cellular Structures, *Computer-Aided Design and Applications*, 4(5): 585-594.

Rosson, M. B. and Carroll, J. M. (2002). Usability engineering: scenario-based development of human-computer interaction. *Interactive technologies*. Morgan Kaufman: San Francisco.

Ruffo, M., Tuck, C., & Hague, R. (2006). Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *220*(9), 1417–1427.

Sabatier, P. A. (2007). Theories of the Policy Process. 2. Boulder, CO: Westview Press.

Sagor, R. (2000). Guiding School Improvement with Action Research. http://www.ascd.org/publications/books/100047/chapters/What-Is-Action-Research%C2%A2.aspx. Date of access: 14 Aug. 2017.

Salonitis, K. (2016). Energy efficiency of metallic powder bed Additive Manufacturing Processes. Handbook of Sustainability in Additive Manufacturing, *Environmental Footprints and Eco-design of Products and Processes*, Vol.2:pp1-29. Singapore: Springer.

Santos, J. R. A. (1999). Cronbach's Alpha: A Tool for Assessing the Reliability of Scales, *Journal of Extension*, 32(2).

Sauro, J. (2015). 5 Types of Qualitative Methods. https://measuringu.com/qual-methods/. Date of access: 11 Aug. 2017.

Serres, N., Tidu, D., Sankare, S. and Hlawka, F. (2011). Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. J. Cleaner Prod 19:1117–1124.

Schelly, C., Anzalone, G., Wiljnen, B and Pearce, J. M. (2015). Open-Source 3D Printing Technologies for Education: Bringing Additive Manufacturing to the Classroom. *Journal of Visual Languages and Computing*, 28: 226-237.

Schmid, Manfred. Amado, Antonio and Wegener, Konrad. (2014). Polymer Powders for Selective Laser Sintering (SLS). *30th International Conference of the Polymer Processing Society*. ETH-Zürich.

Schwerin, A. 2010. Analysis of the Potential Solar Energy Market in the Caribbean. Caribbean Renewable Energy Development Programme (CREDP).

Schubert, C., van Langeveld, M.C. and Donoso, L.A. (2014). Innovations in 3D printing: a 3D overview from optics to organs. *Br Journal Ophthalmol*; 98(2):159–161.

Scott, H. (2009). What is Ground Theory? http://www.groundedtheoryonline.com/what-is-grounded-theory/**.** Date of access: 11 Aug. 2017.

Scott, J., Gupta, N., Weber, C., Newsome, S., Wohlers, T. and Caffrey, T. (2012). Additive manufacturing: Status and Opportunities. IDA – Science and Technology Policy Institute.

Serdar, T. (2016). Educational Challenges in Design for Additive Manufacturing. *American Society for Engineering Education*, *ASEE 123rd Annual Conference and Explosion New Orleans. Los Angelis.* Pp1-10.

Shaw, J. (2017). 3D printing Education: Learn to incorporate 3D Printing in the Class. https://pinshape.com/blog/3d-printing-education-in-the-class/. Date of access 20 Sept. 2018.

Soy, S. K. (1997). The case study as a research method. *Unpublished paper*, University of Texas at Austin. https://www.ischool.utexas.edu/~ssoy/usesusers/l391d1b.htm. Date of access: 11 Aug. 2017.

SPCForexcel. (2016). Are the Skewness and Kurtosis Useful Statistics? https://www.spcforexcel.com/knowledge/basic-statistics/are-skewness-and-kurtosis-useful-statistics. Date of access: 18 May 2018.

SPSS Inc. (2017). IBM SPSS Statistics Version 25, Release 23.0.0, Copyright© IBM Corporation and its licensors. http://www-01.ibm.com/software/analytics/spss/.

Starks, H., Diehr, P and Curtis, J. R. (2009). The challenge of selection bias and confounding in palliative care research. *Journal of Palliat Med*, 12(2):181–187.

Starr, S. (2011). Report on Phase I of IPC Market Research on Electronics Technology Trends: Insights about 10 Key Trends from Interviews with Industry Experts. http://www.fed.de/downloads/TECHTR-10WP.pdf. Date of access: 11 Oct. 2016.

Stewart, P. W. (2017). Small or pilot study, GCRC protocols which propose "pilot studies". Cincinnati Children's Hospital Medical Center.

Stratasys. (2015). Stratasys Direct Manufacturing. 3D Printing: Transforming Manufacturing. Stratasys Direct Inc.

Streiner, D. (2003). Starting at the beginning: an introduction to coefficient alpha and internal consistency. Journal of personality assessment; Vol. 80:99-103.

Struwig, F.W. & Stead, G.B. 2004. *Planning, designing and reporting research*. Cape Town: Pearson Education.

Stucker, Brent. (2012). Additive Manufacturing Technologies: Technology Introduction and Business Implications. University of Louisville. http://www.nap.edu/read/13274/chapter/4. Date of access: 26 August 2016.

Sukamolson, S. (2007). Fundamentals of quantitative research. Chulalongkorn University. https://pdfs.semanticscholar.org/336b/6928c8ee7f3fac6bbeb1e0e1769169c447f7.pdf.

Sullivan, P and McCartney, H. (2017). Integrating 3D printing into an early childhood teacher preparation course: Reflections on practice, *Journal of Early Childhood Teacher Education*, 38(1): 39-51.

Swarup, S. R., Ishant, S. and Shivam, G. (2018). Innovative Training Framework for Additive Manufacturing Ecosystem to Accelerate Adoption of Three-Dimensional Printing Technologies. *3D Printing and Additive Manufacturing Journal*. https://doi.org/10.1089/3dp.2017.0003.

Tang, Y. M. and Mo, J. PT. (2015). Problem Based Learning of Systems Engineering Using Additive Manufacturing Processes. Proceedings of the 11th International Conference on Technology Education (ICTE) in the Asia Pacific Region.

Tashakkori, A and Teddlie, C. 1998. Mixed Methodology: Combining Qualitative & Quantitative Approaches: Sage.

Tavakol, M. and Dennick, R. (2011). Making sense of Cronbach’s alpha. International Journal of Medical Education, Vol.2, pp53-55.

Taylor, S. (2014). First Quantitative 3D Printing Sustainability Study: 3D Printing Industry. https://3dprintingindustry.com/news/quantitative-3dp-sustainability-study-37657/. Date of access: 20 January 2017.

Taylor, D. (2017). The Literature Review: A Few Tips on Conducting It, Health Sciences Writing Centre. University of Toronto. http://advice.writing.utoronto.ca/types-of-writing/literature-review/. Date of access: 15 Aug. 2017.

Thompson, C. B. (2009). Descriptive Data Analysis. Basics of Research Part 13. Air Medical Journal 28(2): 56-59. DOI:10.1016/j.amj.2008.12.001.

Thompson, MK, Moroni, G, Vaneker, T, Fadel, G, Campbell, RI, Gibson, I, Bernard, A, Schulz, J, Graf, P, Ahuja, B & Martina, F. 2016. 'Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints' *C I R P Annals*, pp. 24. DOI: 10.1016/j.cirp.2016.05.004.

Thurn, L. K., Balc, N., Gebhardt, A. and Kessler, J. (2017). Education packed in technology to promote innovations: Teaching Additive Manufacturing based on a rolling Lab. MATEC Web of Conferences, 137, 02013. MTeM - AMaTUC 2017. DOI: 10.1051/matecconf/201713702013.

T. Rowe Price. (Thomas Rowe Price Connections) (2013). A brief history of 3D printing - Infographic. http://www.3dprinter.net/a-brief-history-of-3d-printing-infographic. Date of access: 08 Sept. 2016.

Togwe, T., Tanju, B. and Eveleigh, T. (2018). Using a systems engineering framework for additive manufacturing. *System Engineering*, pp1-10. https://doi.org/10.1002/sys.21447.

Tranchard, S. & Rojas, V. (2015). Manufacturing our 3D future. https://www.iso.org/news/2015/05/Ref1956.html. Date of access: 28 March 2017.

Trochim, W. M. K. (2006). Descriptive Statistics. https://www.socialresearchmethods.net/kb/statdesc.htm. Date of access: 25 August 2018.

Tuck, C., & Hague, R. (2006). The pivotal role of rapid manufacturing in the production of cost-effective customised products. *International Journal of Mass Customisation*, *1*(2-3), 360-373.

Van der Zee, F., Rehfeld, D and Hamza, C. (2015). Open Innovation in Industry, Including 3D Printing. Policy Department A: Economic and Scientific Policy. European Union Documents.

UOS (University of Sheffield). 2016. MSc (Res) Additive Manufacturing and Advanced Manufacturing Technologies. www.sheffield.ac.uk/mecheng/prospectivemsc/additive-manufacturing University of Sheffield. Date of access: 08 Nov. 2016.

Van der Merwe. K. (2011). The development of a lean culture causal framework to support the effective implementation of lean in automotive component manufacturers in South Africa. Port Elizabeth. NMU: [Thesis; PhD].

Van Manen, M. (1990) *Researching Lived Experience: Human science for an action sensitive pedagogy.* London, Ontario: Althouse.

Van Teijlingen, E. R., and Hundley, Vanora. (2001). The importance of pilot studies. http://sru.soc.surrey.ac.uk/SRU35.html. Date of access: 07 July 2016.

Van Wyk, B. (2011). Research design and methods Part I. Post-graduate Enrolment and Throughput. University of Western Cape.

Vayre, B., Vignat, F. and Villeneuve F. (2012). Designing for Additive Manufacturing. 45th CIRP Conference on Manufacturing Systems.

Vayre, B., Vignat, F. and Villeneuve F. (2012). Metallic additive manufacturing: state-of-the-art review and prospects. *Journal of Mechanics & Industry*. Vol. 13:89-96.

Ventola, C. L. (2014). Medical Applications for 3D Printing: Current and Projected Uses. *Pharmacy and Therapeutics*, *39*(10), 704–711.

Von See, C. and Meindorfer, M. (2016). 3D printing: Additive processes in dentistry. Laboratory. http://www.bego.com/fileadmin/user_downloads/Mediathek/Fachartikel/2016/_EN/Lab_May_-_3Dprinting.pdf. Date of access: 16 Oct 2016.

Vosloo, J. J. (2014). Chapter 5: Research Design and Methodology. http://dspace.nwu.ac.za/bitstream/handle/10394/12269/Vosloo_JJ_Chapter_5.pdf?sequence=6.

VUT (2017). Technology Transfer and Innovation. http://www.vut.ac.za/about-tti/. Date of access: 18 October 2017.

Waseem, K., Kazmi, H. A. and Qureshi, O. H. (2016). Innovation in Education - Inclusion of 3D-Printing Technology in Modern Education System of Pakistan: Case from Pakistani Educational Institutes. *Journal of Education and Practice*, 7(36): 1-8. ISSN 2222-1735.

Walter, M., Holmstrom, J., Tuomi, H., and Yrjolo, H. (2004). Rapid manufacturing and its impact on supply chain management. *Pages 9–10 of: Proceedings of the Logistics Research Network Annual Conference*.

Waters, J (2017). Phenomenological Research Guidelines. Capilano University, Canada. https://www.capilanou.ca/psychology/student-resources/research-guidelines/Phenomenological-Research-Guidelines/. Date of access: 11 Aug. 2017.

Westfall, H. Peter. (2014). “Kurtosis as Peakedness”. The American Statistician. 68(3):191-195. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4321753/. Date of access: 15 September 2018.

Widmer, M and Rajan, V. (2016). 3D opportunity for intellectual property risk: Additive manufacturing stakes its claim. A Deloitte series on additive manufacturing. Deloitte University Press.

Williams, C. B., Mistree, F. Rosen, D. W. (2011). A Functional Classification Framework for the Conceptual Design of Additive Manufacturing Technologies. Journal of Mechanical Design, 133(12).

Williams, C. B. and Seepersad, C. C. (2012). Design for additive manufacturing curriculum: A problem- and project-based approach. In *23rd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF*:81-92. (pp. 81-92). University of Texas at Austin. [Abstract].

Williams, G. (2016). Additive manufacturing has huge potential in South Africa. http://www.bdlive.co.za/business/management/2016/08/31/additive-manufacturing-has-huge-potential-in-sa. Date of access: 31 August 2016.

Winters, R., Winters, A. and Amedee, R. G. (2010). Statistics: A brief overview. *The Ochsner Journal*. Vol.10:213–216.

Wittbrodt, B. T., Glover, A. G., Laureto, J., Anzalone, G. C., Oppliger, D., Irwin, J. L. and Pearce, J. M. (2013). Life cycle economic analysis of distributed manufacturing with open-source 2D printers, Mechatronics, 23(6): 713-726.

Wohlers, T. (2004). Additive Manufacturing Report, *Wohlers Annual Worldwide Progress Report,* Wohlers Associates.

Wohlers, T. (2010). State of the Industry, *Wohlers Annual Worldwide Progress Report*, Wohlers Associates.

Wohlers Associates, Inc. (2010). what is Additive Manufacturing? https://wohlersassociates.com/additive-manufacturing.html. Date of access: 11 August 2016.

Wohlers Associates, Inc. (2011). Additive Manufacturing Technology Roadmap for Australia - CSIRO, the Commonwealth Scientific and Industrial Research Organisation.

Wohlers, T. (2012). Wohlers Report 2012: Executive Summary, Wohlers Associates Inc., Fort Collins.

Wohlers, Terry. & Gornet, Tim. (2014). History of additive manufacturing. A Wohlers Report 2014: Wohlers Associates, Inc.

Wohlers Report (2014). 3D Printing and Additive Manufacturing State of Industry. Annual Worldwide Progress Report. Fort Collins: Colorado.

Wohlers Report. (2015). 3D Printing and Additive Manufacturing State of the Industry. Annual Worldwide Progress Report.

Wohlers Report. (2016). 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report.

Wohlers (2016). Wohlers Talk: views, perspective, and commentary from Terry Wohlers. http://wohlersassociates.com/blog/category/additive-manufacturing/page/6/. Wohlers Associates Inc. Date of access: 10 Nov. 2016.

Wohlers, T. and Huff, R. (2017). CSU's Idea2Product Lab. https://wohlersassociates.com/blog/2017/10/csus-idea2product-lab/. Date of access: 21 Dec. 2017.

Wong, K.V and Hernandez, A. (2012). A Review of Additive Manufacturing. *International Scholarly Research Network (ISRN) Mechanical Engineering*.

Wong, D. S. K., Zaw, H. M. and Tao, Z. J. (2014). Additive manufacturing teaching factory: driving applied learning to industry solutions. *Virtual and physical Prototyping*, 9(4): 205-212.

Wu, P., Wang, J. and Wang, W. (2016). A critical review of the use of 3-D printing in the construction industry. Automation in Construction 68:21-31. [Abstract].

Wu, B., Myant, C. and Weider, S. Z. (2017). The value of additive manufacturing: future opportunities. Institute of Molecular Science and Engineering. Imperial College London, Briefing Paper, No. 2.

Yeong, W. Y and Chua, C, K. (2013). A quality management framework for implementing additive manufacturing of medical devices, *Virtual and Physical Prototyping,* 8(3): 193-199, DOI: 10.1080/17452759.2013.838053.

Yong, A, G. and Pearce, S. (2013). A Beginner's Guide to Factor Analysis: Focusing on Exploratory Factor Analysis. *Tutorials in Quantitative Methods for Psychology,* 9(2): 79-94.

Zancul, E. S., Sousa-Zomerb, T. T. and Cauchick-Miguela, P. A. (2017). Project-based learning approach: improvements of an undergraduate course in new product development. *Production Journal,* Vol. 27. DOI: 10.1590/0103-6513.225216.

Zein, I., Hutmacher, D. W., Tan, K. C. and Teoh, S. H. (2002). Fused deposition modelling of novel scaffold architectures for tissue engineering applications. *Biomaterials.* 23(4):1169-1185.

Internet Sources Consulted

2nd Annual 3D printing and Additive manufacturing industrial applications global summit 2014. http://www.3d-printing-additive-manufacturing-2014.com/. Date of access: 30 June 2014.

3DPS (3D Printing from the Scratch). 2015. Types of 3D printers or 3D printing technologies overview. http://3dprintingfromscratch.com/common/types-of-3d-printers-or-3d-printing-technologies-overview/. Date of access: 06 Sept. 2016.

3ders.org. (2014). Loughborough University teams up with Skanska to build commercial 3D concrete printing robot. http://www.3ders.org/articles/20141121-loughborough-university-skanska-to-build-commerical-3d-concrete-printing-robot.html. Date of access: 07 Nov. 2016.

3D Print-Expo. (2017). Laminated Object Manufacturing (LOM). https://3d-expo.ru/en/article/izgotovlenie-obektov-metodom-laminirovaniya-lom-78841. Date of access: 01 March 2019.

3DPR (3D Printing Revolution). 2014. Additive Manufacturing: from prototyping to manufacturing. http://www.3dprintingadditivemanufacturing.org/aerospace/. Date of access: 08 Oct. 2016.

3DSYSTEMS. (2016). Selective Laser Sintering (SLS). http://www.3dsystems.com/resources/information-guides/selective-laser-sintering/sls. Date of access: 11 Sept. 2016.

3PRINTR. (2011). Part 2: Overview of Current 3D Printing Methods. https://www.3printr.com/overview-3d-printing-methods-462146/#4Further_Methods. Date of access: 06 Sept. 2016.

3Printr.com. (2015). German Start-Up teases Silicone prosthesis out of 3D Printers. https://www.3printr.com/german-start-up-teases-silicone-prosthesis-out-of-a-3d-printer-0731571/. Date of access: 27 Oct.

3Printr. (2016). South Africa Launches Additive Manufacturing Strategy. https://www.3printr.com/south-africa-launches-additive-manufacturing-strategy-5742021/. Date of access: 31 August 2016.

3PRINTR. 2011. Part 2: Overview of Current 3D Printing Methods. https://www.3printr.com/overview-3d-printing-methods-462146/#4Further_Methods. Date of access: 06 Sept. 2016.

Agent3D. 2016. 3D in the electronics industry. www.agent3d.de/products.html. Date of access: 12 Oct. 2016.

ALL3DP. 2016. 7 Types of 3D Printer Technology Explained. https://all3dp.com/types-of-3d-printer-technology-explained/. Date of access: 06 Sept. 2016.

AM Magazine (Additive Manufacturing Magazine). 2014. Additive manufacturing: Multiplying Options. www.additivemanufacturing.media/articles/multiplying-options. Date of access: 26 Oct. 2016.

Andale. (2017). Cronbach's Alpha: Simple Definition, Use and Interpretation. http://www.statisticshowto.com/cronbachs-alpha-spss/. Date of access: 29 Aug. 2017.

Anthony, C. (2018). Auburn, partner organizations sign agreements for additive research centres. http://www.eng.auburn.edu/news/2018/07/additive-signing-ceremonies.html. Date of access: 25 Sept. 2018.

Architect. (2015). This Week in Tech: MIT Makes a Multi-Material 3D Printer. http://www.architectmagazine.com/technology/this-week-in-tech-mit-makes-a-multi-material-3d-printer_o. Date of access: 07 Nov. 2016.

Ard-Digital. (2014). 3D Printed Miniature House Project. http://arddigital.co.uk/portfolio/3d-printed-miniature-house-project/. Date of access: 07 Nov. 2016.

ATLASTI. (2017). Qualitative and Quantitative Research: Comparison of Qualitative and Quantitative Research. http://atlasti.com/quantitative-vs-qualitative-research/. Date of Access: 10 Aug. 2017.

Ben-Eliyahu, A. (2014). Understanding different types of research: What's the difference between qualitative and quantitative approaches?. https://chronicle.umbmentoring.org/on-methods-whats-the-difference-between-qualitative-and-quantitative-approaches/. Date of Access: 10 Aug. 2017.

Biddix, P. J. (2009). Writing Research Questions. https://researchrundowns.com/intro/writing-research-questions/. Date of access: 04 July 2016.

Briggs, S. (2014). How 3-D Printing Will Change Education. InformED. http://www.opencolleges.edu.au/informed/features/how-3-d-printing-will-change-education/. Date of access: 09 Nov. 2016.

Cantechletter. (2015). Education Sector On Cusp of Adopting 3D Printing. http://www.cantechletter.com/2015/03/education-sector-on-cusp-of-adopting-3d-printing/. Date of access: 27 June 2016.

Columbus Louis. (2015). 2015 roundup of 3D printing market forecasts and estimates. www.forbes.com/sites/louiscolumbus/2015/03/31/2015-roundup-of-3d-printing-market-forecasts-and-estimates/#f43a3c61dc67. Date of access: 27 June 2016.

CRPM. 2016. Centre for Rapid Prototyping and Manufacturing. http://www.cut.ac.za/crpm/. Date of access: 15 August 2016.

CSC. (2012). 3D Printing and the Future of Manufacturing. http://www.csc.com/innovation/insights/92142-3d_printing_and_the_future_of_manufacturing. Date of access: 09 June 2016.

CSIRO (2015). Commonwealth Scientific and Industrial Research Organisation. Lab 22 offers 3D printing. The Challenge: Lowering capital investment risk. http://www.csiro.au/en/Research/MF/Areas/Metals/Lab22. Date of access: 11 August 2016.

CSU (Colorado State University). 2016. MECH 502 - Advanced/Additive Manufacturing Engineering. www.online.colostate.edu/global/docs/syllabi/MECH502.pdf. Date of access: 08 Nov. 2016.

CSUVentures. (2013). Colorado State University - Idea-2-Product Lab Presents 3D Printing Workshop at CSU. http://csuventures.org/idea-2-product-lab-presents-3d-printing-workshop-at-csu/. Date of access: 21 Dec. 2017.

CustomPartnet. (2009). Additive Fabrication. http://www.custompartnet.com/wu/additive-fabrication. Date of access: 26 Oct. 2016.

David. (2017). Gartner's 2017 3D printing Hype Cycle. https://www.3ders.org/articles/20170804-gartners-2017-3d-printing-hype-cycle.html. Date of access: 22 May 2018.

Davies, S. (2017). End of year report: Exploring the need for education in additive manufacturing. https://www.tctmagazine.com/3d-printing-news/end-of-year-report-education-additive-manufacturing/. Date of access: 11 June 2018.

Debroy, T. (2018). What is the value of all the 3D printed/additively manufactured products per year in the world?. Pennsylvania State University. https://www.researchgate.net/post/What_is_the_value_of_all_the_3D_printed_additively_manufactured_products_per_year_in_the_world. Date of access: 02 July 2018.

DemaPlasTech. (2016). How 3D printers are changing the way we work. http://www.demaplastech.co.za/3d-printers-changing-way-work. Date of access: 20 June 2016.

Dezeen. (2014). Chinese company 3D prints 10 buildings in a day using construction waste. http://www.dezeen.com/2014/04/24/chinese-company-3d-prints-buildings-construction-waste/. Date of access: 07 Nov. 2016.

DIY 3D Printing. 2016. Manufacturing revolution on your desktop. http://diy3dprinting.blogspot.co.za/2016_02_01_archive.html. Date of access: 12 Oct. 2016.

Donaldson, B. (2018). Auburn University offers a Certificate in Additive Manufacturing. https://www.additivemanufacturing.media/articles/auburn-universitys-roadmap-to-additive-manufacturing-education. Date of access: 11 June 2018.

Du Plessis, Sonette. 2015. Is working with 3D printers a dangerous occupation? http://mg.co.za/article/2015-07-30-is-working-with-3d-printers-a-dangerous-occupation. Date of access: 15 August 2016.

Dvorak, P. (2014). 3D print technology allows manufacture of metal products for industrial uses. http://www.windpowerengineering.com/design/mechanical/3d-print-technology-allows-manufacture-metal-products-industrial-uses/. Date of access: 26 Oct. 2016.

Dwight Dart. 2016. University of Virginia’s prototyping lab. http://www.stratasys.com/resources/case-studies/education/university-of-virginia. Date of access: 20 June 2016.

ELSEVIER. (2016). About Scopus. https://www.elsevier.com/solutions/scopus. Date of access: 10 Nov. 2016.

ENGINEERINGNEWS. (2015). South Africa aiming to become a leader in additive manufacturing. http://www.engineeringnews.co.za/article/south-africa-aiming-to-become-a-leader-in-additive-manufacturing-2015-12-04/rep_id:4136. Date of access: 20 June 2016.

Exone. (2016). Education. http://www.exone.com/Industries-Applications/Industries/Education. Date of access: 29 June 2016.

FoodRisc. (2016). Mixed methods research. A resource centre for food risk and benefit communication. http://resourcecentre.foodrisc.org/mixed-methods-research_185.html. Date of access: 11 Aug. 2017.

Gareth van Zyl. (2014). SA 3D printer prices revealed. http://www.fin24.com/Tech/Featured/SA-3D-printer-prices-revealed-20141204. Date of access: 09 June 2016.

Gibilisco Stan (2012). Skewness. http://whatis.techtarget.com/definition/skewness. Date of access: 15 September 2018.

Gizmodo (2015). The World's Biggest Free Form 3D Printer Is Being Used To Build Houses. http://www.gizmodo.com.au/2015/08/the-worlds-biggest-free-form-3d-printer-is-being-used-to-build-houses/. Date of access: 07 Nov. 2016.

Goehrke, S. (2019). A Look Ahead in 3D Printing with Gartner's Pete Basiliere. https://www.fabbaloo.com/blog/2019/1/10/a-look-ahead-in-3d-printing-with-gartners-pete-basiliere. Date of access: 26 Feb. 2019.

Hardcastle, J. L. (2015). Is 3D Printing the Future of Sustainable Manufacturing? http://www.environmentalleader.com/2015/11/is-3d-printing-the-future-of-sustainable-manufacturing/. Date of access: 20 January 2017.

Harrop, Jon. (2015). The fastest growing sectors in 3D printing for 2015. http://www.idtechex.com/emails/5511.asp. Date of access: 28 June 2016.

Heller, Steve. (2014). Why 3D Printing Stocks Could Have a Tremendous Runway for Growth. http://www.fool.com/investing/general/2014/09/09/why-3d-printing-stocks-could-have-a-tremendous-run.aspx. Date of access: 27 June 2016.

How 3D printing will make us self-sufficient," 2013, video on Forbes.com, 6:07, http://landing.newsinc.com/forbes/video.html?vcid=23824226&freewheel=91218&sitesection=forbes. Date of access: 02 Sept. 2016.

HS3DP (Home Shop 3D Printing). 2016. 3D Printing Process and Technologies. http://homeshop3dprinting.com/3d-printing-qa/3d-printing-process-and-technologies/. Date of access: 06 Sept. 2016.

IDTechEx. (2014). Applications of 3D printing - a $7bn market by 2025. http://www.idtechex.com/research/articles/applications-of-3d-printing-a-7bn-market-by-2025-00006565.asp. Date of access: 24 Oct. 2016.

ISO/TC 261 and ASTM F42, (2013). Joint Plan for Additive Manufacturing Standards Development. Volume 2.

ITEEA. (2016). 2016 National Forum on Additive Manufacturing Education and Training. https://www.iteea.org/News/282/102342.aspx. Date of access: 03 May 2017.

Jermann, Michael (2013). Laminated Object Manufacturing. http://www.makepartsfast.com/laminate-object-manufacturing-lom/. Date of access: 10 Sept. 2016.

Joanne, T. (2013). 3D printing may shape a new manufacturing revolution. http://www.engineeringnews.co.za/print-version/getting-real-2013-01-18. Date of access: 21 June 2016.

Kira (2016). Wohlers Report 2016 reveals $1 billion growth in 3D printing industry. http://www.3ders.org/articles/20160405-wohlers-report-2016-reveals-1-billion-growth-in-3d-printing-industry.html. Date of access: 07 Oct. 2016.

Krassenstein, E. (2014). Why 3D Printing Needs to Take Off in Schools Around the World. https://3dprint.com/27743/3d-printing-benefits-schools/. Date of access: 30 June 2016.

LFA (2013). 3D Printing and The Impact That It Will Have On South African Manufacturing. http://www.localisationforafrica.com/news/page/3d-printing-and-the-impact-that-it-will-have-on-south-african-manufacturing. Date of access: 09 June 2016.

Laerd-Statistics. (2018). Measures of central Tendency. https://statistics.laerd.com/statistical-guides/measures-central-tendency-mean-mode-median.php. Date of access: 25 August 2018.

Lenagh, A. (2012). The importance of technology transfer. https://www.unemed.com/blog/the-importance-of-technology-transfer. Date of access: 18 September 2018.

Lidija Grozdanic. (2013). British Architect Designs First 3D Printed Element for Use in the Construction Industry. http://inhabitat.com/british-architect-designs-first-3d-printed-element-for-use-in-the-construction-industry/. Date of access: 07 Nov. 2016.

LIVESCIENCE. (2013). Fused Deposition Modelling: Most Common 3D Printing Method. http://www.livescience.com/39810-fused-deposition-modeling.html. Date of access: 11 Sept. 2016.

Loughborough. (2018). (Loughborough University). Design for Additive Manufacturing. MSc Program. http://www.lboro.ac.uk/study/postgraduate/masters-degrees/a-z/design-additive-manufacture/. Date of access: 10 Oct. 2018.

Hartlieb, M. (2016). Model Spaceships and a Business Model Spring from Students' 3D Printer. University of Advancing Technology (UAT). http://www.stratasys.com/resources/case-studies/education/uat. Date of access: 20 June 2016.

Health.herts. (2017). Qualitative Research: Phenomenology Research. http://www.health.herts.ac.uk/immunology/Qualitative%20research/phenomenology.htm. Date of access: 11 Aug 2017.

Mayer-Brown. (2013). How to Explore the Potential and Avoid the Risks of Additive Manufacturing. https://www.mayerbrown.com/files/uploads/Documents/PDFs/2013/June/Three-Dimensional-Thinking-Brochure_Additive-Manufacturing.pdf.

Metal AM. (2015). Huge Potential of Using Additive Manufacturing to be exhibited at formnext 2015 by the International Tool and Form-Making Industry. http://www.metal-am.com/huge-potential-of-using-additive-manufacturing-to-be-exhibited-at-formnext-2015-by-the-international-tool-and-form-making-industry/. Date of access: 26 Oct. 2016.

MPN (Medical Plastics News) 2016. Why is 2016 the year for additive manufacturing in the medical sector? http://www.medicalplasticsnews.com/why-is-2016-the-year-for-additive-manufacturing-in-the-medic/. Date of access: 27 Oct. 2016.

MRP (Models Rapid Prototype) 2014. Revolutionary biomedical applications for 3D printing. http://www.pdmodels.co.uk/en/blog/3dprinting/biomedical_applications_for_3d_printing.html. Date of access: 27 Oct. 2016.

NAMII. (2013). The National Additive Manufacturing Innovative Institute in Youngstown: What is it? *The Plain Dealer*. http://www.cleveland.com/metro/index.ssf/2013/02/the_national_additive_manufact.html. Date of access: 02 Sept. 2016.

NRFCOMMUNIQUE. (2013). VUT's acquisition to impact on local foundry industries. http://nrfcoms.info/nrfcommunique/vuts-acquisition-to-impact-on-local-foundry-industries/. Date of access: 21 June 2016.

NIU. (Northern Illinois University) 2005. Faculty Development and Instructional Design Center, https://ori.hhs.gov/education/products/n_illinois_u/datamanagement/dctopic.html. Date of access: 16 Aug. 2017.

NSTF (National Science and Technology forum). 2016. Discussion Forum S.E.T for Socio-Economic Growth. Light-based Technologies Innovation Forum - Advances in light-based technologies in solar energy, additive manufacturing and fibre optic communications. http://www.nstf.org.za/discussion-forum/light-based-technologies-innovation-forum/. Date of access: 11 August 2016.

NWU. 2017. (North West University-News). NWU wants to manufacture affordable artificial limbs. http://news.nwu.ac.za/nwu-wants-manufacture-affordable-artificial-limbs. Date of access: 28 March 2017

Optics. (Optics.org) 2017. GE investing $10m in additive manufacturing education. http://optics.org/news/8/1/14. Date of access: 02 May 2017.

OSU 2016. (Oregon State University). OSU Researchers Discuss Sustainability in Additive Manufacturing and New Sustainable Development Methodology. http://additivemanufacturing.com/2016/03/02/osu-researchers-discuss-sustainability-in-additive-manufacturing-and-new-sustainable-development-methodology/. Date of access: 21 March 2017.

Pennstate. (2017). Penn State to offer new additive manufacturing and design graduate degrees. http://www.ime.psu.edu/news/amd-degrees-sp17.aspx. Date of access: 02 May 2017.

Posner, B. (2018). What Does Standard Deviation Mean? http://www.leadershipchallenge.com/resource/what-does-standard-deviation-mean.aspx. Date of access: 07 September 2018

PRNewswire. (2017). UL and Ricoh announce Training Collaboration to focus on Additive Manufacturing education. http://www.prnewswire.com/news-releases/ul-and-ricoh-announce-training-collaboration-to-focus-on-additive-manufacturing-education-300402470.html. Date of access: 02 May 2017.

RAPDASA (The Rapid Product Development Association of South Africa) 2016. Additive Manufacturing in South Africa. http://www.rapdasa.org/aminsa.aspx. Date of access: 09 June 2016.

RAPDASA (The Rapid Product Development Association of South Africa). 2016. What is Additive Manufacturing? http://www.rapdasa.org/am.aspx. Date of access: 09 June 2016.

Rapid. (2016). Industrial Applications of Additive Manufacturing. http://rapid3devent.com/industrial-applications-of-additive-manufacturing/. Date of access: 29 June 2016.

RAPDASA. (2018). Additive manufacturing in South Africa. https://www.rapdasa.org/additive-manufacturing-in-south-africa/. Date of access: 21 September 2018.

RPDLab. 2008. Rapid Product Development Laboratory: promoting accelerated engineering. http://www.rpd.sun.ac.za/. Date of access: 01 July 2016.

Robinson, Adam. (2014). The Democratization of Manufacturing and the Roles of Its Citizens. http://cerasis.com/2014/06/02/democratization-of-manufacturing/. Date of access: 30 August 2016.

SAE International (2015). High-strength aluminium powder developed for additive manufacturing in aerospace, automotive. http://articles.sae.org/14175/. Date of access: 09 Oct. 2016.

Science Forum (2015). Fast 3D Printing of Metal Parts For Aerospace and Medical: A First for Africa. http://www.sfsa.co.za/session-summaries-and-bios/fast-3d-printing-of-metal-parts-for-aerospace-and-medical-a-first-for-africa/. Date of access: 23 June 2016.

Sculpteo. (2014). NightHawk: the first headphones with mass-produced 3D-Printed parts. https://www.sculpteo.com/blog/2014/11/26/nighthawk-audioquest/. Date of access: 12 Oct. 2016.

Sculpteo. (2015). 3D Printing in education: from eLearning to eMaking. https://www.sculpteo.com/blog/2015/11/17/3d-printing-in-education-from-elearning-to-emaking/. Date of access: 09 Nov. 2016.

Shapeways. (2016). Additive Manufacturing. http://www.shapeways.com/additive-manufacturing. Date of access: 11 August 2016.

SSC. (Statistically Significant Consulting). 2017. Statistical Data Analysis. https://www.statisticallysignificantconsulting.com/StatisticalInference.htm. Date of access: 17 Aug. 2017.

Stratasys. (2015). ASTM Additive Manufacturing Standards: What You Need to Know. https://www.stratasysdirect.com/blog/astm-standards/. Date of access: 28 March 2017.

Tess (2017). Russia’s Skoltech opens state-of-the-art AM Lab equipped with Russia's largest metal 3D printer. https://www.3ders.org/articles/20171130-russia-skoltech-opens-state-of-the-art-am-lab-equipped-with-russia-largest-metal-3d-printer.html. Date of access: 24 Sept. 2018.

Tilton, B., Dobner, E. and Holdowsky, J. (2017). 3D opportunity for standards Additive manufacturing measures up. https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-standards-for-3d-printed-products.html. Date of access: 25 Sept. 2018.

UJ. (University of Johannesburg). 2017. Newly launched UJ Makerspace to mould students into entrepreneurs. https://www.uj.ac.za/newandevents/Pages/newly-launched-uj-makerspace-to-mould-students-into-entrepreneurs.aspx. Date of access: 10 August 2018.

UNCC. 2017. (UNC CHARLOTTE). Sociological Research Methods: Empirical Research. http://guides.library.uncc.edu/c.php?g=173030&p=1143848. Date of access: 09 April 2017.

USCLibraries. (University of Southern California). 2017. Organizing Your Social Sciences Research Paper: Quantitative Methods. http://libguides.usc.edu/writingguide/quantitative. Date of access: 17 Aug. 2017.

USCLibraries. (University of Southern California). 2017. Organizing Your Social Sciences Research Paper: Independent and Dependent Variables. http://libguides.usc.edu/writingguide/variables. Date of access: 14 Aug 2017.

VUT (Vaal University of Technology). 2013. Additive Manufacturing. http://www.vut.ac.za/index.php/corporate-services/units/tti/ts/additive-manufacturing. Date of Access: 24 June 2016.

Van Eecke, P. and De Bruyn, J. 2015. 3D printing 101: A typical legal challenges. https://www.dlapiper.com/en/southafrica/insights/publications/2015/05/law-a-la-mode-issue-16/legal-challenges-of-3d-printing/. Date of access: 17 June 2016.

Whiteclouds. (2015). Digital Light Processing (DLP). https://www.whiteclouds.com/3dpedia-index/digital-light-processing-dlp. Date of access: 11 Sept. 2016.

Wild, S. 2014. South African companies take to 3D printing. http://www.mediaclubsouthafrica.com/tech/4026-south-african-companies-take-to-3d-printing. Date of access: 27 June 2016.

Wisdom, J. and Creswell, J. W. (2013). Mixed Methods: Integrating Quantitative and Qualitative Data Collection and Analysis While Studying Patient-Centred Medical Home Models. Rockville, MD: Agency for Healthcare Research and Quality. AHRQ Publication No. 13-0028-EF.

Wyse, S. E. (2011). What's the difference between qualitative and quantitative research? https://www.snapsurveys.com/blog/qualitative-vs-quantitative-research/. Date of access: 17 Aug. 2017.

Zaiontz, C. (2015). Null and Alternative Hypotheses. Real Statistics Using Excel. http://www.realstatistics.com/hypothesis-testing/null-hypothesis/. Date of access: 13 Oct. 2016.

Zelinski, P. (2016). Educators and Industry Discuss Need for Engineering Education to Adapt to AM. http://www.additivemanufacturing.media/blog/post/educators-and-industry-discuss-need-for-engineering-education-to-adapt-to-am. Date of access: 03 May 2017.

Appendix A

Questionnaire for the Survey on Additive Manufacturing Education

No. ☐

Research Questionnaire

NORTH-WEST UNIVERSITY
YUNIBESITI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT
POTCHEFSTROOM CAMPUS
Faculty of Engineering

Ref: Doctoral Research - Additive Manufacturing Education

Dear Respondents:

Research Background

Additive Manufacturing (AM) is also known as 3D Printing technology; is defined as the process of joining materials to make objects from 3D model data, and it is usually layer upon layer. In the past 10 years, additive manufacturing technology has gained a significant interest in academic and industries due to its ability to create complex geometries with customizable material properties. Additive manufacturing is so relatively new, and the greatest impact may come through the introduction of additive manufacturing education to university curriculum.

Additive Manufacturing education can be described as a platform through which additive manufacturing technology (3D Printing) is being introduced into the educational sector to promote and enhance the Science, Technology, Engineering and Mathematics (STEM) programs at different educational levels such as (Colleges and Universities).

In South Africa, additive manufacturing education in the academia and undergraduate teaching is still at an infancy stage; though this technology is a global technology with a lot of relevance in the industry. There is a need for inclusion of this technology in the curriculum of the relevant courses for the country to fully reap its enormous benefits (Akinlabi, 2016).

More so, as additive manufacturing technology grows in South Africa, the need for educated personnel in the field is becoming more apparent. Recently, during stakeholders' workshop, “AM Education” was highlighted as one of the main priorities to ensure successful adoption of AM technology in South Africa (du Preez *et al.* 2016).

The problem is that as additive manufacturing or 3D Printing technology becomes increasingly adopted/used in education and industry, the demand for experienced additive manufacturing practitioners and systems continues to grow. Therefore, as a university that have established an additive manufacturing/3D printing lab; what are the impact, application and limitations of additive manufacturing education at the university since its inception.

The Aim of the Research

The aim of this study is to investigate/examine the impact and application of Additive Manufacturing education at South African Universities using Selected Universities as the Case Study for this research (Such as “Idea 2 Product (I2P) Lab at the Vaal University of Technology and NWU-Pukke 3D Printing Center at North-West University); and to further develop a framework for Additive Manufacturing education.

Procedure

Should you agree to participate in this study, it will be expected of you to complete the questionnaire as sincerely and honestly as possible. **Completing the questionnaire may take approximately 15 minutes of your time.** In order to insure your anonymity, please do not write your name on the questionnaire or attached document. You will not receive any payment for your participation in the survey; it will be considered a voluntary act that will be embraced with gratitude. The research findings will be available on request from the researcher; see details contact below.

Confidentiality

Even though the responses from your participation will be documented, analyzed, interpreted and presented; you may take assurance that your name will never be revealed and the data obtained from you will be handled with utmost confidentiality. Completing this questionnaire shows that you have given your consent that your information will be used mainly for this research purpose. I truly appreciate your willingness to participate in this important research project and the valuable time you are willing to commit in completing this research questionnaire. The outcome of this research will identify the need for additive manufacturing education to be included in the university curriculum and an effective framework would be designed in this regards.

Kind Regards

Researcher:

Name: Micheal O, ALABI;
Degree program: PhD in Eng[Development and Management Engineering].
Email: 25756982@nwu.ac.za or micalabs@gmail.com;
Cell no: 0744833400.

SECTION A - BIOGRAPHICAL INFORMATION

1. Gender: Male [1] Female [2]

2. Age: 15-20 years [ ] 21-25 years [ ] 26-30 years [ ] 31-35 years [ ] 36-40 years [ ] 41-45 years [ ] 46-50 years [ ]
Others [ ] years.

3. You are kindly advice to complete the one applicable to you

3a. Name of Your University: [ ]

3b. Name of Your Organization or company: [ ]

4. You are advise to only complete the one applicable to you in this section:

4a. For Undergraduate Student (Year of Study): circle appropriately [1] [2] [3] [4]

4b. For Postgraduate Student: circle appropriately Honours [1] Masters [2] Doctoral [3]

4c. Provide your field of study, write in the space from list below: [ ]

(1) Mechanical Engineering (2) Industrial Engineering (3) Electrical Engineering (4) Computer Engineering
(5) Chemical Engineering (6) Information Technology (7) Information Engineering/Systems (8) Material Engineering
(9) Science related degree (10) Others

4d. For University Staff: Tick/Write the appropriate one: AM researcher or expert [1]

Lecturer [2] Prof/ Associate Prof/ Senior lecturer/Lecturer/ Assistant Lecturer **Others** [3]

5. Level of Experience with AM education/technology: Basic [ ] Intermediate [ ] AM expert [ ] Novice [ ]

SECTION B - PERCEPTIONS TOWARDS THE DEVELOPMENT OF ADDITIVE MANUFACTURING EDUCATION FRAMEWORK

	1. Additive Manufacturing (AM) technology - This section presents fundamental questions on additive manufacturing. Please indicate your level of agreement with the following statements by circling the appropriate options.	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
1.1	Additive manufacturing has been found to be useful in the following sectors:					
	a.) Manufacturing	1	2	3	4	5
	b.) Industrial design	1	2	3	4	5
	c.) Engineering	1	2	3	4	5
	d.) Dental and medical	1	2	3	4	5
	e.) Automotive	1	2	3	4	5
	f.) Aerospace	1	2	3	4	5
	g.) Education	1	2	3	4	5
1.2	Additive manufacturing technology has been found to:					
	a.) Reduces waste material,	1	2	3	4	5
	b.) Brings down labour costs	1	2	3	4	5
	c.) Speeds up the development	1	2	3	4	5
	d.) Speeds up the test phase	1	2	3	4	5
	e.) Allows for product customization	1	2	3	4	5
	f.) Ability to make complex metal parts	1	2	3	4	5
1.3	Additive manufacturing creates opportunity to improve new product development	1	2	3	4	5
1.4	AM education enhances the Science & Engineering degree at the university in South Africa	1	2	3	4	5
1.5	Most Science & Engineering students at SA universities have fundamental knowledge of AM	1	2	3	4	5
1.6	A number of Science & Engineering students at South African universities have access to AM technology for design purposes.	1	2	3	4	5
1.7	A number of Science & Engineering students at our university have access to AM technology for prototyping purposes	1	2	3	4	5
1.8	From Advance Manufacturing Perspective, AM is regarded as a Sustainable Technology	1	2	3	4	5
1.9	Establishment of "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Center" or 3D Printing Lab at other Universities in South Africa is having greater impact on Science & Engineering Education.	1	2	3	4	5

2

2 Technology Transfer – This section presents questions on technology transfer; the purpose of this section is to know respondent perspective as relating to "technology transfer". Please, indicate your level of agreement with the following statements by circling the appropriate options.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.1	Technology transfer is the process of passing theoretical and practical skills, knowledge, manufacturing processes &technologies from the owner of a technology to a wider range of users.	1	2	3	4	5
2.2	Technology transfer ensures that:					
	a.) Scientific and technological development become more available in industry	1	2	3	4	5
	b.) Skills development of the university academic staff.	1	2	3	4	5
2.3	Technology transfer plays a major role:					
	a.) In the development of AM education at the university	1	2	3	4	5
	b.) In the integration of AM education at the university	1	2	3	4	5
2.4	University-industry collaboration on additive manufacturing processes will:					
	a.) Further enhance the university academic relations with industry	1	2	3	4	5
	b.) Further enhance the university students relations with industry	1	2	3	4	5
	c.) Promote more research at the university	1	2	3	4	5
	d.) Attract more scholarships/bursary to the universities	1	2	3	4	5
	e.) Attract more internships for the student at the university	1	2	3	4	5
2.5	3D printing bureau or organization could provide students, academic and industry engineers:					
	a.) with hands-on experience	1	2	3	4	5
	b.) with on-the-job experience.	1	2	3	4	5

3. Educational curriculum - This section presents questions on AM education curriculum and the need for its inclusion in the educational system at the South Africa universities. Please indicate your level of agreement with the following statements by circling the appropriate options.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
3.1	More educated personnel in the field of additive manufacturing are needed in South Africa as the technology is rapidly growing at an exponential across industries.	1	2	3	4	5
3.2	Additive Manufacturing education could be included in the relevant:					
	a.) Undergraduate science and engineering courses at the universities	1	2	3	4	5
	b.) Postgraduate science and engineering courses at the universities	1	2	3	4	5
3.3	An introduction of AM technology courses as full-semester courses at the university would enhance and promote the educational aspect of the technology	1	2	3	4	5
3.4	An introduction of AM technology courses as full-semester courses would serve as mean to allow science and engineering students to develop interest in AM and creates career path in AM.	1	2	3	4	5
3.5	A suitable short-course program should be designed for engineers in industry which could provide them with:					
	a.) An exposure to AM machines (3D printers)	1	2	3	4	5
	b.) A hands-on-experiences of AM technology	1	2	3	4	5
	c.) An exposure to design and simulation techniques.	1	2	3	4	5
3.6	Entry level FDM desktop AM/3D printing machine is considered suitable for a Additive Manufacturing education at the University Level.	1	2	3	4	5
3.7	All the 3D printing Labs at South Africa Universities, specifically the "Idea 2 Product" Lab at VUT and NWU Pukke 3D Printing Center equipping students and professionals with both basic and in-depth knowledge of the AM technology	1	2	3	4	5

4. AM In-house facilities – This section presents questions that relates to in-house AM/3D printing facilities at South African university to promote AM education and research activities. Please, indicate your level of agreement with the following statements by circling the appropriate options.		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
4.1	Acquisition in-house AM/3D printing facilities at the university fosters:					
	a.) Effective additive manufacturing education	1	2	3	4	5
	b.) Effective additive manufacturing research	1	2	3	4	5
4.2	Establishment of AM/3D printing labs at the university would increase students interest in AM or 3D printing technology	1	2	3	4	5
4.3	A cutting edge in-house AM/3D printer facilities at our university supports:					
	a.) Teaching	1	2	3	4	5
	b.) Learning	1	2	3	4	5
	c.) Academic research	1	2	3	4	5
	d.) Industry collaboration	1	2	3	4	5
4.4	In-house AM facilities at selected universities in South Africa are available for students and academic:					
	a.) For design and prototyping purposes	1	2	3	4	5
	b.) For final product printing purposes	1	2	3	4	5
	c.) For teaching and research activities (i.e. Masters and PhD student research)	1	2	3	4	5
	d.) For final or fourth year projects	1	2	3	4	5

5. AM Research and development (R&D) – This section presents questions that relates to research and development of AM which should serve as a prominent driver for technological innovation. Please indicate your level of agreement with the following statements by circling the appropriate options..		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
5.1	In the advancement of AM; Research and development is playing a vital roles:					
	a.) In the creation of additive manufacturing standards (ISO/ASTM)	1	2	3	4	5
	b.) For registration of additive manufacturing patent	1	2	3	4	5
	c.) For innovative and technological advancement of AM	1	2	3	4	5
5.2	Inclusion of a MSc program in Additive Manufacturing at selected university in South Africa Would further strengthen AM Research and development at the universities/industries.	1	2	3	4	5
5.3	Annual fund and grant from the Department of Science and Technology (DST) would boost AM research output at various universities in South Africa.	1	2	3	4	5
5.4	Annual fund and grant from National Research Foundation (NRF) increases AM research output at various universities in South Africa.	1	2	3	4	5

Open-Ended Questions

6a. Do you think inclusion of Additive Manufacturing education to science and engineering curriculum at South African universities is a good idea ?

....

....

....

6b. Does the "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Center" or 3D Printing Lab at your University is having **positive impacts** on Additive Manufacturing education or **Promoting** AM education?

....

....

....

THANK YOU FOR COMPLETING THIS QUESTIONNAIRE

Appendix B

Descriptive Statistics of the questionnaire for the survey data

	N	Minimum	Maximum	Mean	Std. Deviation
B1.1a	130	3	5	4.40	0.579
B1.1b	130	2	5	4.32	0.659
B1.1c	130	3	5	4.42	0.594
B1.1d	130	1	5	4.22	0.856
B1.1e	130	2	5	4.25	0.758
B1.1f	130	2	5	4.28	0.780
B1.1g	130	2	5	4.29	0.731
B1.2a	130	2	5	4.02	0.807
B1.2b	130	2	5	4.07	0.717
B1.2c	130	2	5	4.18	0.628
B1.2d	130	2	5	4.05	0.746
B1.2e	130	3	5	4.28	0.650
B1.2f	130	2	5	4.32	0.684
B1.3	130	3	5	4.38	0.613
B1.4	130	2	5	4.12	0.822
B1.5	130	1	5	3.62	1.102
B1.6	130	1	5	3.72	1.093
B1.7	130	1	5	3.62	1.015
B1.8	130	1	5	3.94	0.795
B1.9	130	3	5	4.28	0.705
B2.1	130	1	5	4.42	0.703
B2.2a	130	2	5	4.34	0.677
B2.2b	130	2	5	4.29	0.698
B2.3a	130	2	5	4.22	0.729
B2.3b	130	1	5	4.25	0.748
B2.4a	130	2	5	4.29	0.603
B2.4b	130	3	5	4.28	0.560
B2.4c	130	2	5	4.26	0.642
B2.4d	130	2	5	4.07	0.837
B2.4e	130	2	5	4.03	0.880
B2.5a	130	3	5	4.28	0.625
B2.5b	130	1	5	4.01	0.944
B3.1	130	3	5	4.49	0.574
B3.2a	130	3	5	4.36	0.623
B3.2b	130	2	5	4.32	0.613
B3.3	130	3	5	4.28	0.610
B3.4	130	3	5	4.32	0.610
B3.5a	130	2	5	4.40	0.592
B3.5b	130	3	5	4.36	0.584

B3.5c	130	1	5	4.28	0.705
B3.6	130	3	5	4.32	0.610
B3.7	130	2	5	4.25	0.740
B4.1a	130	2	5	4.35	0.644
B4.1b	130	2	5	4.32	0.635
B4.2	130	3	5	4.35	0.569
B4.3a	130	2	5	4.22	0.647
B4.3b	130	2	5	4.19	0.660
B4.3c	130	2	5	4.30	0.579
B4.3d	130	3	5	4.34	0.565
B4.4a	130	2	5	4.22	0.718
B4.4b	130	2	5	4.17	0.779
B4.4c	130	2	5	4.09	0.782
B4.4d	130	2	5	4.03	0.787
B5.1a	130	2	5	4.08	0.689
B5.1b	130	3	5	4.12	0.630
B5.1c	130	3	5	4.22	0.570
B5.2	130	3	5	4.15	0.660
B5.3	130	3	5	4.32	0.600
B5.4	130	3	5	4.44	0.584
Valid N (listwise)	130				

Appendix C

Descriptive Statistics for Skewness and Kurtosis for the survey data

	Valid N	Skewness		Kurtosis	
	Statistic	Statistic	Std. Error	Statistic	Std. Error
B1.1a	130	-0.332	0.212	-0.735	0.422
B1.1b	130	-0.773	0.212	0.958	0.422
B1.1c	130	-0.454	0.212	-0.659	0.422
B1.1d	130	-1.201	0.212	1.857	0.422
B1.1e	130	-0.771	0.212	0.190	0.422
B1.1f	130	-1.045	0.212	0.918	0.422
B1.1g	130	-1.123	0.212	1.736	0.422
B1.2a	130	-0.748	0.212	0.436	0.422
B1.2b	130	-0.871	0.212	1.481	0.422
B1.2c	130	-0.341	0.212	0.311	0.422
B1.2d	130	-0.531	0.212	0.193	0.422
B1.2e	130	-0.359	0.212	-0.707	0.422
B1.2f	130	-0.662	0.212	-0.052	0.422
B1.3	130	-0.438	0.212	-0.640	0.422
B1.4	130	-0.897	0.212	0.607	0.422
B1.5	130	-0.407	0.212	-0.783	0.422
B1.6	130	-0.804	0.212	-0.105	0.422
B1.7	130	-0.342	0.212	-0.791	0.422
B1.8	130	-0.265	0.212	-0.061	0.422
B1.9	130	-0.449	0.212	-0.900	0.422
B2.1	130	-1.354	0.212	-0.900	0.422
B2.2a	130	-0.687	0.212	0.035	0.422
B2.2b	130	-0.611	0.212	-0.212	0.422
B2.3a	130	-0.494	0.212	-0.542	0.422
B2.3b	130	-0.889	0.212	1.392	0.422
B2.4a	130	-0.444	0.212	0.584	0.422
B2.4b	130	-0.025	0.212	-0.504	0.422
B2.4c	130	-0.477	0.212	0.203	0.422
B2.4d	130	-0.615	0.212	-0.207	0.422
B2.4e	130	-0.615	0.212	-0.335	0.422
B2.5a	130	-0.292	0.212	-0.632	0.422
B2.5b	130	-0.857	0.212	0.218	0.422
B3.1	130	-0.594	0.212	-0.626	0.422
B3.2a	130	-0.437	0.212	-0.644	0.422
B3.2b	130	-0.524	0.212	0.504	0.422
B3.3	130	-0.231	0.21	-0.580	0.422
B3.4	130	-0.296	0.212	-0.625	0.422
B3.5a	130	-0.629	0.212	0.751	0.422
B3.5b	130	-0.272	0.212	-0.684	0.422
B3.5c	130	-0.990	0.212	2.350	0.422
B3.6	130	-0.296	0.212	-0.625	0.422
B3.7	130	-0.795	0.212	0.416	0.422
B4.1a	130	-0.823	0.212	1.253	0.422
B4.1b	130	-0.747	0.212	1.283	0.422
B4.2	130	-0.173	0.212	-0.715	0.422
B4.3a	130	-0.587	0.212	0.923	0.422
B4.3b	130	-0.721	0.212	1.407	0.422
B4.3c	130	-0.384	0.212	0.817	0.422
B4.3d	130	-0.122	0.212	-0.688	0.422
B4.4a	130	-0.743	0.212	0.593	0.422
B4.4b	130	-0.806	0.212	0.484	0.422

B4.4c	130	-0.658	0.212	0.201	0.422
B4.4d	130	-0.733	0.212	0.511	0.422
B5.1a	130	-0.390	0.212	0.511	0.422
B5.1b	130	-0.093	0.212	-0.488	0.422
B5.1c	130	-0.018	0.212	-0.278	0.422
B5.2	130	-0.166	0.212	-0.708	0.422
B5.3	130	-0.269	0.212	-0.623	0.422
B5.4	130	-0.468	0.212	-0.684	0.422

Appendix D

Detailed feedback received for section B of the questionnaire with percentages for each questions and total number of respondents that participated in the survey.

Questions by Section	Number of Respondents	Detailed Feedback with percentage and total number respondents				
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Section B – Sub-section 1: – Additive Manufacturing Technology						
1.1 Additive manufacturing has been found to be useful in the following sectors:						
a). Manufacturing	130	0.0%, = 0	0.0%, = 0	4.6%, = 6	50.8%, = 66	44.6%, = 58
b). Industrial Design	130	00%, = 0	1.5%, = 2	6.2%. = 8	51.5%, = 67	40.8%, = 53
c). Engineering	130	0.0%, = 0	0.0%, = 0	5.4%, = 7	47.7%, = 62	46.9%, = 61
d). Dental and Medical	130	1.5%, = 2	1.5%, = 2	13.8%, =18	39.2%, = 51	43.8%, = 57
e). Automotive	130	0.0%, = 0	2.3%, = 3	12.3%, = 16	43.8%, = 57	41.5%, = 54
f). Aerospace	130	0.0%, = 0	3.8%, =5	8.5%, = 11	43.1%, = 56	44.6%, = 58
g). Education	130	0.0%, = 0	3.8%, = 5	4.6%, = 6	50.0%, = 65	41.5%, = 54
1.4 Additive Manufacturing technology has been found to:						
a). Reduces waste material	130	0.0%, = 0	6.2%, = 8	13.1%, = 17	53.8%, = 70	26.9%, = 35
b). Brings down labour cost	130	00%, = 0	4.6%, = 6	8.5%, = 11	62.3%, = 81	24.6%, = 32
c). Speeds up the development	130	0.0%, = 0	0.8%, = 1	10.0%, = 13	60.0%, = 78	29.2%, = 38
d). Speeds up the test phase	130	0.0%, = 0	3.1%, = 4	16.2%, = 21	53.8%, = 70	26.9%, = 35
e). Allows for product customization	130	0.0% = 0	0.0%, = 0	10.8%, = 14	50.0%, = 65	39.2%, = 51
f). Ability to make complex metal parts	130	0.0%, = 0	0.8%, = 1	10.0%, = 13	45.4%, = 59	43.8%, = 57
1.3 Additive manufacturing creates opportunity to improve new product development	130	0.0%, = 0	0.0%, = 0	6.9%, = 9	48.5%, = 63	44.6%, = 58
1.4 AM education enhances the Science & Engineering degree at the university in South Africa	130	0.0%, = 0	6.2%, = 8	10.0%, = 13	50.0%, = 65	33.8%, = 44
1.5 Most Science & Engineering students at SA universities have fundamental knowledge of AM.	130	2.3%, =3	16.9%, = 22	21.5%, = 28	34.6%, = 45	24.6%, = 32
1.6 A number of Science & Engineering students at South African universities have access to AM technology for design purposes.	130	3.8%, = 5	13.8%, = 18	12.3%, = 16	46.2%, = 60	23.8%, = 31
1.7 A number of Science & Engineering students at our university have access to AM technology for prototyping purposes.	130	0.8%, = 1	16.9%, = 22	22.3%, = 29	40.0%, = 52	20.0%, = 26
1.8 From Advance Manufacturing Perspective, AM is regarded as a Sustainable Technology.	130	0.8%, = 1	0.0%, = 0	30.0%, = 39	43.1%, = 56	26.2%, = 34
1.9 Establishment of "Idea 2 Product (I2P) Lab at VUT" and "NWU Pukke 3D Printing Centre" or 3D Printing Lab at other Universities in South Africa is having greater impact on Science & Engineering Education.	130	0.0%, = 0	0.0%, = 0	14.6%, = 19	43.1%, = 56	42.3%, = 55

Section B – Sub-section 2: – AM Technology Transfer						
2.1 Technology transfer is the process of passing theoretical and practical skills, knowledge, manufacturing processes &technologies from the owner of a technology to a wider range of users.	130	0.8%, = 1	0.0%, = 0	7.7%, = 10	39.2%, = 51	52.3%, = 68
2.2 Technology transfer ensures that:						
a.) Scientific and technological development become more available in industry	130	0.0%, = 0	0.8%, = 1	9.2%, = 12	45.4%, = 59	44.6%, = 58
b.) Skills development of the university academic staff.	130	0.0%, = 0	0.8%, = 1	11.5%, = 15	45.4%, = 59	42.3%, = 55
2.3 Technology transfer plays a major role:						
a.) In the development of AM education at the university	130	0.0%, = 0	0.8%, = 1	15.4%, = 20	44.6%, = 58	39.2%, = 51
b.) In the integration of AM education at the university	130	0.8%, = 1	0.0%, = 0	13.8%, = 18	44.6%, = 58	40.8%, = 53
2.4 University-industry collaboration on additive manufacturing processes will:						
a.) Further enhance the university academic relations with industry	130	0.0%, = 0	0.8%, = 1	5.4%, = 7	57.7%, = 75	36.2%, = 47
b.) Further enhance the university students relations with industry	130	0.0%, = 0	0.0%, 0	5.4%, = 7	60.8%, = 79	33.8%, = 44
c.) Promote more research at the university	130	0.0%, = 0	0.8%, = 1	8.5%, = 11	54.6%, = 71	36.2%, = 47
d.) Attract more scholarships/bursary to the universities	130	0.0%, = 0	4.6%, = 6	17.7%, = 23	43.8%, = 57	33.8%, = 44
e.) Attract more internships for the student at the university	130	0.0%, = 0	6.2%, = 8	18.5%, = 24	41.5%, = 54	33.8%, = 44
2.5 3D printing bureau or organization could provide students, academic and industry engineers:						
a.) with hands-on experience	130	0.0%, = 0	0.0%, = 0	9.2%, = 12	53.1%, = 69	37.7%, = 49
b.) with on-the-job experience.	130	0.8%, = 1	8.5%, = 11	13.8%, = 18	43.1%, = 56	33.8%, = 44
Section B – Sub-section 3: – AM Educational Curriculum						
3.1 More educated personnel in the field of additive manufacturing are needed in South Africa as the technology is rapidly growing at an exponential across industries.	130	0.0%, = 0	0.0%, = 0	3.8%, = 5	43.1%, = 56	53.1%, = 69
3.2 Additive Manufacturing education could be included in the relevant:						
a.) Undergraduate science and engineering courses at the universities	130	0.0%, = 0	0.0%, = 0	7.7%, = 10	48.5%, = 63	43.8%, = 57
b.) Postgraduate science and engineering courses at the universities	130	0.0%, = 0	0.8%, = 1	5.4%, = 7	54.6%, = 71	39.2%, = 51
3.3 An introduction of AM technology courses as full-semester courses at the university would enhance and promote the educational aspect of the technology.	130	0.0%, = 0	0.0%, = 0	8.5%, = 11	55.4%, = 72	36.2%, = 47
3.4 An introduction of AM technology courses as full-semester courses would serve as mean to allow science and engineering students to develop interest in AM and creates career path in AM.	130	0.0%, = 0	0.0%, = 0	7.7%, = 10	53.1%, = 69	39.2%, = 51
3.5 A suitable short-course program should be designed for engineers in industry which could provide them with:						
a.) An exposure to AM machines (3D printers)	130	0.0%, = 0	0.8%, = 1	3.1%, = 4	51.5%, = 67	44.6%, = 58
b.) A hands-on-experiences of AM technology	130	0.0%, = 0	0.0%, = 0	5.4%, = 7	53.1%, = 69	41.5%, = 54

c.) An exposure to design and simulation techniques.	130	0.8%, = 1	0.0%, = 0	10.0%, = 13	49.2%, = 64	40.0%, = 52
3.6 Entry level FDM desktop AM/3D printing machine is considered suitable for Additive Manufacturing education at the University Level.	130	0.0%, = 0	0.0%, = 0	7.7%, = 10	53.1%, = 69	39.2%, = 51
3.7 All the 3D printing Labs at South Africa Universities, specifically the "Idea 2 Product" Lab at VUT and NWU Pukke 3D Printing Centre equipping students and professionals with both basic and in-depth knowledge of the AM technology	130	0.0%, = 0	2.3%, = 3	10.8%, = 14	46.2%, = 60	40.8%, = 53
Section B – Sub-section 4: – AM In-House Facilities						
4.1 Acquisition in-house AM/3D printing facilities at the university fosters:						
a.) Effective additive manufacturing education	130	0.0%, = 0	1.5%, = 2	4.6%, = 6	51.5%, = 67	42.3%, = 55
b.) Effective additive manufacturing research	130	0.0%, = 0	1.5%, = 2	4.6%, = 6	54.6%, = 71	39.2%, = 51
4.2 Establishment of AM/3D printing labs at the university would increase students interest in AM or 3D printing technology.	130	0.0%, = 0	0.0%, = 0	4.6%, = 6	55.4%, = 72	40.0%, = 52
4.3 A cutting edge in-house AM/3D printer facilities at our university supports:						
a.) Teaching	130	0.0%, = 0	1.5%, = 2	7.7%, = 10	58.5%, = 76	32.3%, = 42
b.) Learning	130	0.0%, = 0	2.3%, = 3	6.9%, = 9	60.0%, = 78	30.8%, = 40
c.) Academic research	130	0.0%, = 0	0.8%, = 1	3.8%, = 5	60.0%, = 78	35.4%, = 46
d.) Industry collaboration	130	0.0%, = 0	0.0%, = 0	4.6%, = 6	56.9%, = 74	38.5%, = 50
4.4 In-house AM facilities at selected universities in South Africa are available for students and academic						
a.) For design and prototyping purposes	130	0.0%, = 0	2.3%, = 3	10.0%, =13	50.8%, = 66	36.9%, = 48
b.) For final product printing purposes	130	0.0%, = 0	3.8%, = 5	11.5%, = 15	48.5%, = 63	36.2%, = 47
c.) For teaching and research activities (i.e. master's and PhD student research)	130	0.0%, = 0	3.8%, = 5	14.6%, = 19	50.0%, = 65	31.5%, = 41
d.) For final or fourth year projects	130	0.0%, = 0	5.4%, = 7	13.1%, = 17	54.6%, = 71	26.9%, = 35
Section B – Sub-section 5: – AM Research and Development (R&D)						
5.1 In the advancement of AM; Research and development is playing vital roles:						
a.) In the creation of additive manufacturing standards (ISO/ASTM)	130	0.0% = 0	1.5%, = 2	15.4%, = 20	56.9%, = 74	26.2%, = 34
b.) For registration of additive manufacturing patent	130	0.0% = 0	0.0% = 0	14.6%, = 9	59.2%, = 77	26.2%, = 34
c.) For innovative and technological advancement of AM	130	0.0% = 0	0.0% = 0	7.7%, = 10	63.1%, = 82	29.2%, = 38
5.2 Inclusion of ~~a~~an MSc program in Additive Manufacturing at selected university in South Africa Would further strengthen AM Research and development at the universities/industries.	130	0.0% = 0	0.0% = 0	15.4%, = 20	54.6%, = 71	30.0%, = 39
5.3 Annual fund and grant from the Department of Science and Technology (DST) would boost AM research output at various universities in South Africa.	130	0.0% = 0	0.0% = 0	6.9%, = 9	53.8%, = 70	39.2%, = 51
5.4 Annual fund and grant from National Research Foundation (NRF) increases AM research output at various universities in South Africa.	130	0.0% = 0	0.0% = 0	4.6%, = 6	46.9%, = 61	48.5%, = 63

Appendix E

1. The Inter-Item Correlation Matrix for Sub-section 1 – AM Technology

This sub-section contained 4 inter-item correlation matrices for each construct as listed below:

First Construct - Inter-Item Correlation Matrix

	B1.1a	B1.1b	B1.1c	B1.1d	B1.1e	B1.1f	B1.1g
B1.1a	1.000	0.601	0.595	0.335	0.304	0.330	0.253
B1.1b	0.601	1.000	0.672	0.465	0.526	0.502	0.451
B1.1c	0.595	0.672	1.000	0.502	0.477	0.462	0.486
B1.1d	0.335	0.465	0.502	1.000	0.643	0.566	0.279
B1.1e	0.304	0.526	0.477	0.643	1.000	0.589	0.303
B1.1f	0.330	0.502	0.462	0.566	0.589	1.000	0.383
B1.1g	0.253	0.451	0.486	0.279	0.303	0.383	1.000

Second Construct - Inter-Item Correlation Matrix

	B1.2a	B1.2b	B1.2c	B1.2d	B1.2e	B1.2f
B1.2a	1.000	0.454	0.316	0.295	0.302	0.300
B1.2b	0.454	1.000	0.557	0.443	0.323	0.144
B1.2c	0.316	0.557	1.000	0.528	0.331	0.191
B1.2d	0.295	0.443	0.528	1.000	0.485	0.229
B1.2e	0.302	0.323	0.331	0.485	1.000	0.367
B1.2f	0.300	0.144	0.191	0.229	0.367	1.000

Third Construct - Inter-Item Correlation Matrix

	B1.3	B1.4	B1.8	B1.9
B1.3	1.000	0.497	0.318	0.205
B1.4	0.497	1.000	0.296	0.306
B1.8	0.318	0.296	1.000	0.349
B1.9	0.205	0.306	0.349	1.000

Fourth Construct - Inter-Item Correlation Matrix

	B1.5	B1.6	B1.7
B1.5	1.000	0.698	0.625
B1.6	0.698	1.000	0.763
B1.7	0.625	0.763	1.000

2. The Inter-Item Correlation Matrix for Sub-section 2 – AM Technology Transfer

This sub-section contained 3 inter-item correlation matrices for each construct as listed below:

First Construct - Inter-Item Correlation Matrix

	B2.1	B2.2a	B2.2b	B2.3a	B2.3b
B2.1	1.000	0.593	0.552	0.510	0.508
B2.2a	0.593	1.000	0.822	0.553	0.554
B2.2b	0.552	0.822	1.000	0.602	0.529
B2.3a	0.510	0.553	0.602	1.000	0.809
B2.3b	0.508	0.554	0.529	0.809	1.000

Second Construct - Inter-Item Correlation Matrix

	B2.4a	B2.4b	B2.4c	B2.4d	B2.4e
B2.4a	1.000	0.693	0.602	0.451	0.334
B2.4b	0.693	1.000	0.546	0.503	0.375
B2.4c	0.602	0.546	1.000	0.529	0.507
B2.4d	0.451	0.503	0.529	1.000	0.765
B2.4e	0.334	0.375	0.507	0.765	1.000

Third Construct - Inter-Item Correlation Matrix

	B2.5a	B2.5b
B2.5a	1.000	0.482
B2.5b	0.482	1.000

3. The Inter-Item Correlation Matrix for Sub-section 3 – AM Educational Curriculum

This sub-section contained 3 inter-item correlation matrices for each construct as listed below:

First Construct - Inter-Item Correlation Matrix

	B3.2a	B3.2b	B3.3	B3.4
B3.2a	1.000	0.687	0.530	0.452
B3.2b	0.687	1.000	0.526	0.492
B3.3	0.530	0.526	1.000	0.575
B3.4	0.452	0.492	0.575	1.000

Second Construct - Inter-Item Correlation Matrix

	B3.5a	B3.5b	B3.5c
B3.5a	1.000	0.789	0.550
B3.5b	0.789	1.000	0.772
B3.5c	0.550	0.772	1.000

Third Construct - Inter-Item Correlation Matrix

	B3.6	B3.7
B3.6	1.000	0.542
B3.7	0.542	1.000

4. The Inter-Item Correlation Matrix for Sub-section 4 – AM In-House Facilities

This sub-section contained 3 inter-item correlation matrices for each construct as listed below:

First Construct - Inter-Item Correlation Matrix

	B4.1a	B4.1b	B4.2
B4.1a	1.000	0.755	0.552
B4.1b	0.755	1.000	0.654
B4.2	0.552	0.654	1.000

Second Construct - Inter-Item Correlation Matrix

	B4.3a	B4.3b	B4.3c	B4.3d
B4.3a	1.000	0.574	0.488	0.478
B4.3b	0.574	1.000	0.517	0.511
B4.3c	0.488	0.517	1.000	0.683
B4.3d	0.478	0.511	0.683	1.000

Fourth Construct - Inter-Item Correlation Matrix

	B4.4a	B4.4b	B4.4c	B4.4d
B4.4a	1.000	0.583	0.584	0.427
B4.4b	0.583	1.000	0.687	0.472
B4.4c	0.584	0.687	1.000	0.638
B4.4d	0.427	0.472	0.638	1.000

5. The Inter-Item Correlation Matrix for Sub-section 5 – AM Research and Development

Inter-Item Correlation Matrix

	B5.1a	B5.1b	B5.1c	B5.2	B5.3	B5.4
B5.1a	1.000	0.515	0.451	0.401	0.333	0.359
B5.1b	0.515	1.000	0.512	0.499	0.372	0.283
B5.1c	0.451	0.512	1.000	0.472	0.361	0.343
B5.2	0.401	0.499	0.472	1.000	0.604	0.476
B5.3	0.333	0.372	0.361	0.604	1.000	0.610
B5.4	0.359	0.283	0.343	0.476	0.610	1.000

Appendix F

Applications of Additive Manufacturing at Selected South African Universities: Promoting Additive Manufacturing Education

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Abstract

Purpose – This paper aims to provide a comprehensive overview of the recent applications of additive manufacturing research and activities within selected universities in the Republic of South Africa.

Design/Methodology/Approach – The paper is a general review of additive manufacturing (AM) education, research and development effort within selected South African universities. The paper begins by looking at several support programmes and investments on AM technologies by South Africa Department of Science and Technology (DST). The paper presents South Africa's AM journey till date, and recent global development in AM education. Next, the paper reviewed the recent research activities on AM at four selected universities, SA AM road-map and South African AM strategy. The future prospects of AM education and research are then evaluated through a SWOT analysis. Finally, the paper looks at the sustainability of AM from education perspective.

Findings – The main lessons have been learnt from South Africa AM research activities within selected universities as follows: AM research activities at SA's universities serve as a platform to promote AM education, several support programmes and investments from SA's DST has greatly enhanced the growth of AM across different sectors such as medical, manufacturing, industrial design, tooling, jewellery, education and etc. The government support has also assisted in the actualization of "Aeroswift" project, the world's largest and fastest state-of-the-art AM machine that can 3D print metal parts. The AM research activities within SA universities have shown that it is not too late for any developing countries to start and embrace AM technology both in academia and industry. Based on the SWOT analysis, the future prospects of AM technology in SA is very brighter.

Practical Implications – Researchers/readers from different background such as (academic, industrial and governmental) will be able to learn important lesson from SA additive manufacturing journey and success of SA AM researchers/practitioners. The paper will allow the giant players in AM technologies and business to see great opportunities to invest in AM education and research at all educational levels (high schools, colleges and universities) in SA.

Originality/Value – The authors believe that the progress of AM education and research activities within the SA's universities shows good practice and achievement over the years in both the applications of AM and the SA additive manufacturing strategy introduce to promote AM research and the educational aspect of the technologies.

Keywords: Additive Manufacturing Education, Additive Manufacturing, 3D printing, South African Universities.

Paper Type – General Review

1. Introduction

Additive Manufacturing (AM), also referred to as 3D printing; is a process of creating a physical object from 3-dimensional digital model layer upon layer. Additive Manufacturing has been identified as a 21st century emerging technology and is becoming popular around the world within the academic and manufacturing industries. AM has a wide variety of potential application areas such as medical and dental, automotive, aerospace, general manufacturing, etc. AM education can be introduced into the universities systems through cutting edge research in collaboration with the university's academic and industry partners. AM (previously also referred to as Rapid

Prototyping) in South Africa started in 1991 with a Single 3D System SLA 250. Research and development has been identified as a promising field where AM is influencing the education sector.

South Africa (SA) is one of the active countries on the Africa continent promoting Additive Manufacturing (AM) research; both in academia and industry. Through various support programmes, SA's Department of Science and Technology (DST) has invested significantly towards research in AM. The SA AM Strategy also aims to promote AM education and awareness. SA researchers have built the world's largest and fastest state-of-the-art AM machine that can 3D print metal parts using a powder bed fusion approach. The project is called "Aeroswift", and was officially launched in 2011 through collaboration with Aerosud (an aviation manufacturing solutions provider) and the SA Council for Scientific and Industrial Research (CSIR), and funded by the SA's DST (Scott, 2017b; Oberholzer, 2018). In a recent report from the Industrial Development Corporation (IDC) in 2017, it is mentioned that an investment of R17 million, (equivalent to approximately $1.2 million USD) in a metal 3D printing a start-up facility that manufacture metal parts, called "Metal Heart". These investments are part of South African government strategy to create a competitive advantage in AM and to provide jobs in priority industries, e.g. the oil and gas industry, energy industry, fuel cells, medical devices and nanotech industry. The IDC has also been tasked to develop a New Industries Programme for SA, as part of its preparation to be able to participate in the 4th Industrial Revolution.

According to Wohlers (2016) "SA has grown to become a leader in additive manufacturing and although the adoption of the AM technology is not as deep and widespread as it is in the United States and parts of Europe, the work is just as advanced and impressive". Moreover, SA has become a benchmark for other countries who are late adopters of AM technology to follow and emulate (De Beer, 2011). Currently, AM is an exciting development in the education sector across the world. It is also referred to as an emerging technology that would revolutionize colleges, universities and schools, and it has brought great possibilities to different educational disciplines ranging from Science, Engineering, Technology, Geography, Geology, Biology, Chemistry, Mathematics, Fine Art, etc. (Martin, 2013; Sculpteo, 2015). For an effective use of AM in the education sector, a non-competitive collaboration between AM companies (i.e. the AM systems and materials manufacturer) and the educational institutes would be crucial to develop industry standard educational curricula and in educating the industry workforce (QTR, 2015).

During a panel discussion focussing on AM in SA held by the SA National Science and Technology Forum (NSTF, held in March 2016), it was identified that the SA AM sector is led by higher education institutions (i.e. the universities) and science councils. The leading institutions in additive manufacturing/3D printing in SA are Central University of Technology (CUT) and Vaal University of Technology (VUT) where products are being manufactured daily for various industries/sectors. CUT focuses primarily on serving the medical industry while VUT services the tooling and casting industries. Also, North-West University (NWU) and Stellenbosch University (SU) are part of the AM role-players in SA (NSTF, 2016). Therefore, four universities' research activities were reviewed and considered owing to their active research, in-house industrial grade AM platforms (including entry-level 3D printers) available at these universities.

The paper is arranged as follows: Section 2 introduces SA's AM journey; Section 3 presents the SA AM Strategy; Section 4 describes some recent developments in AM education; Section 5 presents some recent AM applications at selected South African universities; Section 6 presents sustainability of AM from an education perspective, followed by conclusions.

2. South Africa's Additive Manufacturing Journey

SA has been active in AM for the past 26 years. Although SA had a late start with rapid prototyping (now known as AM), SA started with AM approximately 10 years after the technology has been accepted by international community (De Beer, 2011). It was recorded that from 1991 to 1994 only three AM systems were available within South Africa (De Beer, 2011). The first 3D printing system was introduced in 1991 (3D Systems SLA 250). In 1994, the Council for Scientific and Industrial Research (CSIR) bought two FDM 1500 machines, which were later upgraded to FDM 1650s. AM was initially introduced into the universities and other research institutions with the aim of assisting their cooperation with the industry (De Beer, 2011).

In 1996, the CUT purchased two AM systems; a Sanders ModelMaker and SLA 250; the CSIR purchased an SLA 500 in the same year. In 1998, CUT purchased a DTM Sinterstation and this brought the number of AM systems in SA to seven. As at 1998, out of the seven AM systems in South Africa, six of the additive manufacturing systems were owned by academic or research organizations (De Deer, 2011). In 2000, the Rapid Product Development Association of South Africa (RAPDASA) was officially launched. RAPDASA is the representative body of the AM and product development of community in South Africa (Du Preez and De Beer, 2006). RAPDASA played a significant role in raising awareness through annual conference and international ties such as the Global Alliance of Rapid Prototyping Associations (Kunniger, 2015).

Steady growth of AM systems took the overall number of AM machines to 17 in 2003. Out of the 17 AM systems available in 2003, only 2 were owned by private organization while 15 of the machines were with the universities and science/research councils (Campbell & De Beer, 2005; Wohlers, 2004). In 2004, the trend towards AM/3D printing technology in SA continued to grow exponentially (Campbell & De Beer, 2005). The market of AM systems, especially the desktop 3D printing machines in SA continued to increase. Since 1994 to 2004, it was estimated that 32 AM machines were available (Campbell & De Beer, 2005). Between 2004 and 2008, there were approximately 138 AM machines available across South Africa (Campbell, 2011). In 2013, approximately 1500 AM machines were available, and in 2015, it was estimated that 3500 AM machines were in circulation (De Beer, 2015b) as shown in figure 1. Out of the 3500 AM machines recorded between 1994 and 2015, 85% of the AM machines were entry-level desktop 3D printers and 15% represented high-end industrial grade AM machines.

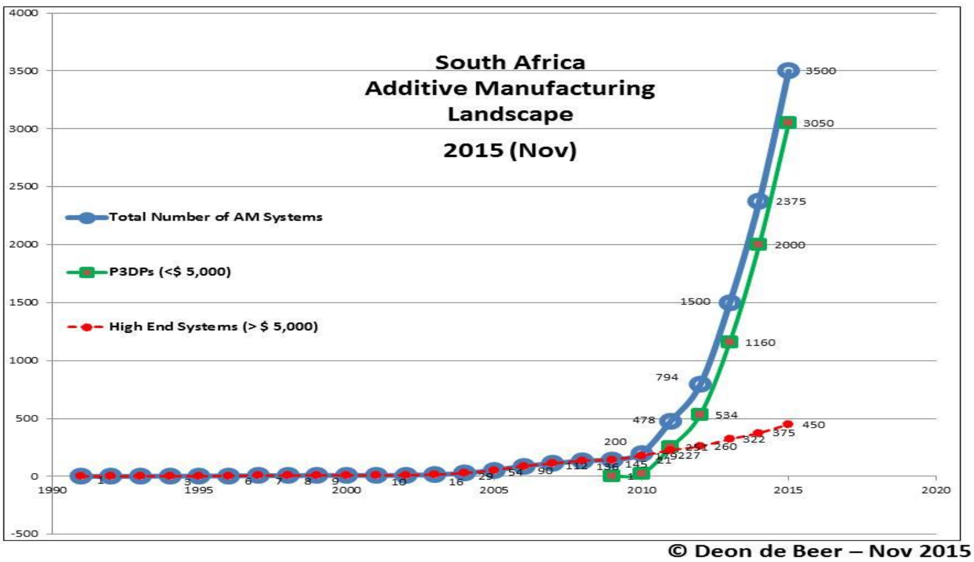

Figure 1: South African Additive Manufacturing Landscape/Growth of 3D Printers, 1991-2015
(Supplied by: Deon de Beer).

A reasonable number of these AM systems are in science councils and higher education institutions in South Africa. It is evident that the AM landscape and 3D printing sales in South Africa experienced a significant growth within the past 26 years, which implies that the future of AM in South Africa is very bright compared to other African countries. More so, the number of high-end industrial grade AM machines at CUT and VUT have increased exponentially in recent years. Recently, SA has developed a new high speed and large volume AM system for metal parts. The system is being developed in partnership with the National Laser Center (NLC) at the CSIR and Aerosud. . NLC and Aerosud aims to develop AM techniques and the world's largest 3D printer (Wild, 2014). The project is called "Aeroswift" and being funded by SA's Department of Science and Technology (Science Forum, 2015). Aeroswift AM Machine has a large build volume of up to (2m x 0.6m x 0.6m), which results in the production of large 3D printed parts. In 2017, Aeroswift AM system produced their first three demonstrator parts which includes (a pilot's throttle lever, a condition lever grip which is part of the throttle assembly and a fuel tank pylon bracket). The Aerosud and CSIR team have discussed with Boeing and Airbus as relating the use of 3D

printed titanium parts in the aircraft, which will reduce the weight significantly, and lower the production cost, the commercial production is expected to begin in 2019.
According to Koslow (2016) SA's public sector has invested around 358 million Rand (about $24.5 million USD) in AM technology research and development, and is likely to increase in the near future. In addition, the DST committed ZAR 30.7 million (EUR 2 million) towards a collaborative research and development programme in 2016 (Williams, 2016). Williams (2016) also stressed that "the collaborative programme for AM (CPAM) research and development programme will focus on research and development; innovation support in AM of qualified titanium medical implants and aerospace components and polymer AM, as well as design for AM expertise". This investment has imbued SA with specific world-class capabilities, positioning the country to participate in sub-sectors with high growth potential in additive manufacturing on a global scale.

As part of the new developments and opportunities in AM in SA in 2016, an initiative called "Platforum" started to experiment with 3D printing of 99.99% pure platinum for the very first time. Platinum has been one of the major precious metal materials used mostly in the production of expensive jewellery, catalytic converters for the automotive industry and fuel cell membranes. It is also used in the oil and gas industry, medicine, electronics and also for high-performance aerospace parts. Platinum has greater benefits and it is extremely corrosion-resistant (Scott, 2017b). The "Platforum" team currently explores the possibility of using the benefits of platinum as leverage to investigate whether platinum could be additively manufactured/3D printed. The "Platforum" team is a partnership between CUT, NWU, VUT; and Lonmin, a platinum producer (Scott, 2017a). This achievement by the "Platforum" has made South Africa to showcase the potential of 3D printing of Platinum Group Metals (PGMs) and the first pure platinum 3D printed ring (as shown in figure 2) was showcased during the annual RAPDASA conference in November 2017, held at International Convention Centre in Durban, South Africa.

(a) (b)

Figure 2: South Africa First Pure Platinum 3D Printed Ring (a) shows the processes of 3D printing the ring using EOSINT M 280 machine from EOS; (b) shows the 3D printed ring using 99.99% of platinum powder material. (Scott, 2017a).

3. South African Additive Manufacturing Road-Map

As part of the effort of the SA government and DST to promote and enhance the AM revolution in the country. Both within the academic and industry spheres, there is a need to develop a comprehensive and easily to implement AM technology road-map. During 2012 RAPDASA conference and AGM, it was recommended to develop a SA National AM Road-map. In 2013, the DST approved the development of SA AM Road-map (Du Preez and De Beer, 2015a). The purpose of SA AM Technology Road-map was to guide "SA AM players to identify economic opportunities, address technology gaps, focus on development programmes, and make investment decisions and to enable local SA companies and industry sectors to become global leaders in selected areas of AM (Du Preez and De Beer, 2015a).

The road-map would allow the local SA companies and Industry sectors to become world leaders in selected areas of AM technology. In 2015, the SA AM technology road-map recommendation was presented to the DST and RAPDASA (Du Preez and De Beer, 2015a). The road-map comprised of four focus areas (Qualified AM parts for medical and aerospace, AM for impact in traditional manufacturing sectors, New AM materials and technologies and SMME development) as shown in figure 3. The road-map attempted to create an enabling capability development environment and promote AM education at the colleges and universities.

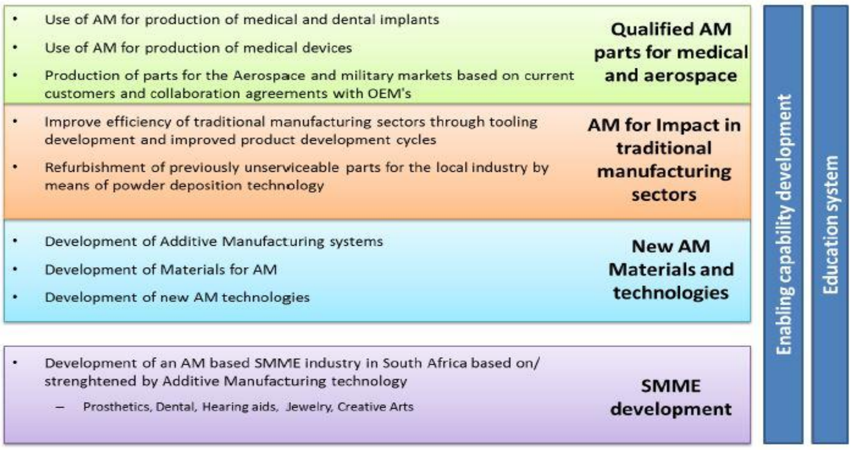

Figure 3: Recommendations of the South African AM Technology Roadmap. (De Beer & Du Preez, 2015a)

Alongside the SA AM Road-map (Du Preez and De Beer (2015a), a commercialisation of AM platforms for South African industries (shown in figure 4), was also suggested. The concept of a national AM Centre of Competence (AMCoC) framework was suggested to primarily serve as the implementation vehicle for SA AM Road-map. Almost all the SA universities were included as part of collaborators for the SA AMCoC as shown in figure 4 (Du Preez and De Beer, 2015a). The target SA industry in the AMCoC are chemical and Power Generation, Aerospace and Medical, and Automotive and Consumer) and the SA supplier development part conmprises of Southern Implants, Aerosurd, Denel, PolyOAK, Rely, and Castco. The industrial and commercialisation group within the AMCoC framework consists of Aerosud, Southern implants, Daliff, ATTRI, DST, DTI, IDC, NFTN, RAPDASA, and TLIU.

The technology development aspect of the AMCoC framework centred on five areas AM applications (i.e. Advanced Tooling, Footwear, Medical Implant & Devices, Aerostructures and Direct End-Use with focus on SMME). The support platform is classified into five areas such as process and product development, design, simulation and modelling, materials development and characterisation, laboratories and R&D facilities and Human capacity development. As part of long-term plan of the SA AM strategy, selected SA universities and research institutes were included in the SA AM centre of competence, that is, CUT, VUT, SU, NWU, Council for Scientific and Industrial Research, University of Cape Town, University of Pretoria, Wits University, Nelson Mandela University, Durban University of Technology, University of Johannesburg.

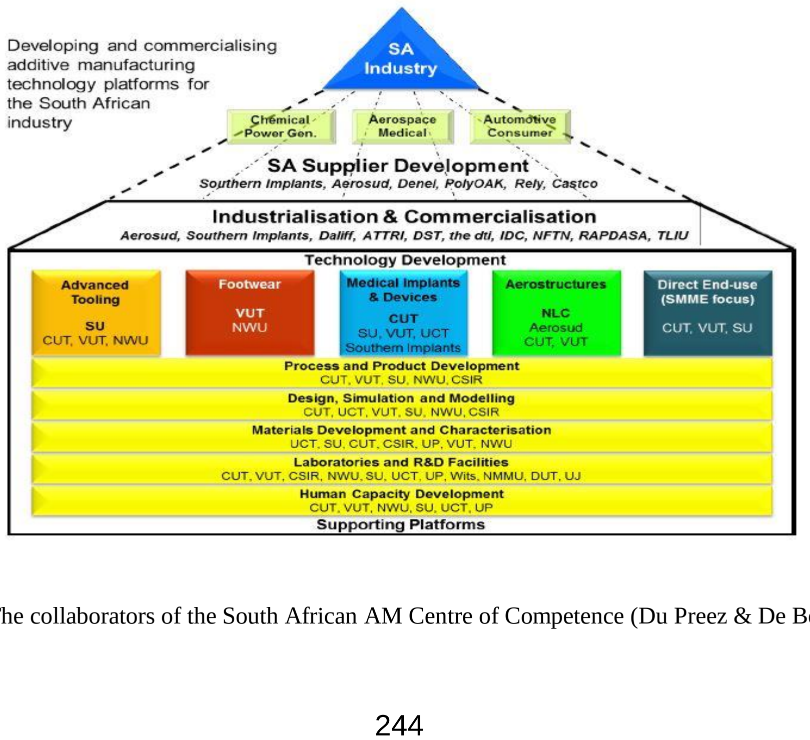

Figure 4: The collaborators of the South African AM Centre of Competence (Du Preez & De Beer, 2015)

4. Recent Global Development in Additive Manufacturing Education

AM education can be described as a platform or vehicle through which AM technology are being introduced to the educational sector to promote and enhance the Science, Technology, Engineering and Mathematic (STEM) programmes and degrees at various educational levels, from primary school, high school, colleges, universities. In addition, educational and training programmes should also be directed to artisans, technicians, technologists, engineers and scientists already working in diverse industries. Active AM research or technology transfer activities at the universities and research councils/institutes worldwide can also serve as a platform to bring AM education to the classroom. AM education would promote high school and university students' interest in AM technologies and allow them to choose a career path in AM. Globally, many industrial sectors are rapidly adopting AM while some industries are using AM technology to complement their existing traditional manufacturing systems.

Therefore, there is a need for graduates with basic knowledge and hands-on AM experience, that would allow them to take up position at various AM industries, internationally. SA is not an exception of this development. Industries and companies within South Africa are embracing this technology. AM education and training need to be introduced to high schools and universities, and more so, an AM curriculum needs to be developed, suitable for SA educational context. This initiative was started at the VUT. A 3D printing technology laboratoriums (Idea 2 Product Lab™) have been established in approximately six high schools as at 2017, which was to be continued in 2018. Introduction of AM technology - especially desktop 3D printing machines at high school, would encourage younger generations to develop interest in science and engineering education, higher education and finally careers.

According to Platt (2015) a study conducted by a data analytics company shows that 35% of recent engineering job opportunities in certain fields require basic knowledge/skills of AM technology; such field includes: Biomedical, Electrical, Industrial, Software engineering and transportation industries; and the findings also shows most of these companies are having difficulties in finding suitable engineering candidates with AM skills to take up the AM related positions (Platt, 2015; Huston *et al* 2015). Despite the tremendous growth in the field of additive manufacturing technology, there are few studies that centred on AM education per se. Some of the recent studies in the field in the field of AM with direct focus at AM education at the universities across the world were identified below.

According to Williams and Seepersad (2012) AM education is of crucial importance because lack of knowledge or experience with AM technologies is one of the barriers to achieve widespread adoption of AM. Williams and Seepersad (2012) addressed the "design for additive manufacturing" and curriculum for undergraduate/postgraduate AM courses at the University of Texas, illustrated using both problem-based and project-based approaches which enables students with opportunities to acquire hand-on experience with AM. Their general class structures for AM curriculum focuses on the following topics, namely: Identifying AM opportunities, AM project planning and economic, AM concepts generation, AM embodiment design, and AM detailed design. Introduction of this AM curriculum has greatly assisted the students in applying their newly-acquired knowledge of design for AM and to carry out their final year project through the whole product development process, that is, from idea inception to AM to final testing (Williams and Seepersad, 2012).

Dickens *et al* (2016) publication on AM education in the United Kingdom shows the journey of AM education in the United Kingdom The paper is a comprehensive review of various AM research activities in the UK. The AM education started in the UK in March 1992 with a seminar organized by the institution of Mechanical Engineers coupled with an industrial exhibition stand. the UK has AM Research landscape that includes educational activities and organization involvement (Dickens *et al*, 2016). Despeisse and Minshall (2017) study titled 'skills and education for AM: a review of emerging issues' addresses the present talent shortage needed to deliver necessary skills and knowledge for an effective deployment of AM technologies. The study identifies some key matters or issues in the education environment needed to address the current skill gap and barriers in adopting and exploiting AM technology. Despeisse and Minshall (2017) study reviewed the current educational and training program in AM for both undergraduate and postgraduate courses ranging from full academic program to short course for professionals in industry. The study made recommendations for AM education program to enhance the AM skills for students, lectures, designers, engineers and managers in industries (Despeisse and Minshall, 2017).

Waseem *et al* (2016) study on AM education titled "Innovation in Education - Inclusion of 3D-Printing Technology in Modern Education System of Pakistan: Case from Pakistani Educational Institutes". The primary aim of the study was "to examine and shed the light over current education system of Pakistan without opting modern 3D printing technology in the classroom learning and how it can be beneficial for educationist". Their study analysed the Pakistan traditional education system when compared to the international present-day education system with AM/3D printing technology, and the way this technology has revolutionized today educational system (Waseem *et al*, 2016). More so, Radharamanan (2017) study on AM in manufacturing education, implementation and development of a new course at the Mercer University, School of Engineering. The study shows the significance of incorporating AM in the manufacturing curriculum of engineering education; A senior level AM elective course was developed to provide students taking the AM elective course with hands-on-experience. In the course, the students learnt the fundamental AM processes and were trained using different design tools like (123D Design, Pro E, Netfabb and etc).

Drakoulaki (2017) study titled "3D printing as learning activity in the higher education", a case study of a robotics prototyping course at the university of Oslo, Norway. The study focuses on the learning aspect of AM education among higher education students; the study addressed the problem of "how 3D printing may support learning and knowledge construction in the university and how this activity relates to students". More so, Drakoulaki (2017) study explore the research question on how 3D printing technology does serve as a tool for learning and also how does the lecturers and students perceive the significance of the 3D printing for learning purpose at the university.

Furthermore, Minetola *et al* (2015) conducted a research titled "impact of additive manufacturing on engineering education – evidence from Italy". The study aimed to evaluate the way direct access to AM machines could impact future mechanical engineering education using Master of Science program in Mechanical Engineering at the 'The Polytechnic University of Turin in Italy' as the case study; The Polytechnic University of Turin is a top Italian university, which is partly public engineering university. The research methodology for the study was 'questionnaire survey'; which consists both closed and open - ended questions. The questionnaire was designed specifically to evaluate the relevance of an entry-level AM machines within the learning environment and as a tool for project development. The outcome of the research shows positive impact on mechanical engineering student using AM technologies at the university (Minetola *et al*, 2015).

In recent times, AM education has drawn the attention of various industries and universities across the world; and this has led to much collaboration between the universities and industries. For example, in 2017, General Electric (GE) has committed $10 million over the next five years to school and college programs in the US to develop future talent in 3D printing/production technologies through additive manufacturing education. GE additive believes that "enabling educational institutions to provide access to 3D printers will help accelerate the adoption of AM worldwide" and this collaboration is to further strengthen GE's position in rapidly growing markets of additive manufacturing (Optics, 2017). Similarly, as part of industry's collaboration on AM education program, in 2017, two United States-based companies announced a training collaboration to focus on additive manufacturing education. The purpose of the collaboration is to promote the proper usage and advancement of AM technologies and drive AM knowledge into the manufacturing sector faster and more consistently. Their training curriculum includes foundational level learning and more complex design, material, process, business and quality and safety courses in additive manufacturing (PRNewswire, 2017).

In SA, established or training programmes tailored towards the needs of the AM education and industry is limited, because the technology is still very new (Du Preez *et al.* 2016). Du Preez *et al.* (2016) explain that "as the technology grows in SA, the need for educated personnel in the field is becoming more apparent". During a stakeholder workshops in 2016, they identified some essential measures to ensure AM education at different levels (for instance, from Primary/Secondary Schools, to Higher Education Institutions (HEI) and diverse industries) as listed below (Du Preez *et al.* 2016):

- To develop a short, medium and long-term educational framework for AM;

- To ensure school-level interventions to facilitate exposure to the technology;
- Provide widespread access to the technology at school level, for example through the establishment of computer labs and Computer Aided Design (CAD) software courses;
- To establish a national AM curriculum for all design and engineering schools at the colleges and universities.
- To establish a dedicated bursary programme for both pre-and post-graduate studies in the field of AM and 3D printing;
- To secure National Research Foundation (NRF) and DST Research Chairs for AM; and, to establish a national AM centres at strategic locations.

Some universities across the globe have introduced courses in AM, for example, in the United States, Colorado State University has introduced a 'MECH 502' - Advanced/Additive Manufacturing Engineering' as part of the courses undertaken master program in Mechanical Engineering (CSU, 2016), University of Maryland started a Master's Program in AM for fall 2017 which was designed purposely working engineers and technical staffs with core courses such as: engineering design method, engineering decision making, engineering optimization, applied machine learning for engineering and design, additive manufacturing and advanced mechanics of materials, Penn State University introduced additive manufacturing and design master's degree in 2017 fall (Pennstate, 2017). In the United Kingdom, University of Sheffield started a Master program by research [MSc (Res)] in Additive Manufacturing and Advanced Manufacturing Technologies within the Department of Mechanical Engineering (UOS, 2016), Derby University is starting a Master of Science (MSc Advanced Materials and Additive Manufacturing) in 2018 and Loughborough University is starting an MSc in Design for Additive Manufacture in 2019 with the aim to cover key areas such as digital design and fabrication (Loughborough, 2018). China universities such as Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, and South China University of Technology; have embraced AM education (Dickens *et al*, 2012; Lin *et al*, 2012 and Hague *et al*, 2016).

As AM education is rapid growing worldwide, Briggs (2014) identifies certain benefits of AM in the educational sector as highlighted below:

- Increase student exposure, and enhancing creativity,
- Provide adequate educational technology, and gives balance curriculum,
- Encouraging sharing and collaboration, and to increase greater level of customization.
- Making manufacturing and designing a common knowledge
- To successfully prepare students for design and careers in AM technology

In 2016, the National Forum on AM Education and Training was held at the Penny State University, which brought so many educators and industry together to address the need for AM technologies to be adapted into engineering education. The forum explores the question of *how should engineering and manufacturing education adapt to the advance of AM?* (Zelinski, 2016). The outcomes of the conference show the need for (STEM) educators, university academics, researchers and industry to collectively adapt and develop educational strategies to prepare students for 21st century STEM manufacturing techniques such as AM (ITEEA, 2016).

5. Recent Applications of Additive Manufacturing Research Activities at Selected South Africa Universities.

In a study conducted by Campbell *et al* (2011) showed that major universities in SA have a strong presence in manufacturing-related research, and the study also established that approximately 48% of all SA universities have AM/3D printing facilities in-house. Because of this, AM education within the science and engineering is rapidly growing among undergraduate students; also, the postgraduate students and academic staffs are using the facilities for research purposes. The key reasons for AM technology at the SA universities is to promote AM education and selected universities in SA have "high-end industrial AM machines" and "entry-level desktop 3D printers" for academics, research and commercial purposes. The selected universities in SA includes Central University of Technology (CUT), Vaal University of Technology (VUT), North-West University (NWU) and Stellenbosch University. These universities were selected because of the availability of AM in-house facilities at their campuses and active AM research group; and the facilities comprises of both high-end industrial grade and entry-level AM machines. This section of this paper presents the recent applications AM research activities at the selected SA universities mentioned earlier.

5.1 The Central University of Technology

CUT is a university of technology in Bloemfortein; a city in central South Africa. In the past two decades, the university has involved in an extensive research in AM and CUT is regarded as AM centre. In 1997, Centre for Rapid Prototyping and Manufacturing (CRPM) was established. At that time, AM technologies was in its infancy stage worldwide. CRPM serves as a system of commercial centre and bridging the gap between the faculty, academic and industry (Jordaan, 2010). The CRPM proved that enabling 'Rapid Manufacturing' platform can create room for Higher Education Institutions to operate as entrepreneurial universities (ENUs) in South Africa (Jordaan, 2010). CRPM does commercial and research work using rapid prototyping, rapid tooling, rapid manufacturing and medical product development technologies to enhance education and research development (De Beer, 2010). The prototypes manufactured are being used by industrial and product designers for final prototypes before mass production of tooling (De Beer, 2010).

Currently, the CRPM have more than ten high-end industrial grade additive manufacturing machines which makes CRPM one of the best AM centres with world-class facilities within the Southern Hemisphere. At the CRPM, the AM research focuses on three AM areas, such as: *medical applications, prototyping and rapid tooling* with funding support from the DST, Technology Innovation Agency (TIA), NRF and SA Medical Research Council (SAMDC). Based on various AM research on medical applications, the centre became the first in South Africa to receive ISO 13485 certification for 3D printing of medical devices and first AM centre with ISO 13485 certification in Africa.

CUT was awarded a Research Chair in Medical Product Development with grant through the DST in 2012, and this boosted the university research activities for medical purposes using AM technology (Helsel, 2015) and in 2018, CUT became Research Chair in Innovation and Commercialization of AM.. According to Jordaan (2010) the unique role of AM technology at CUT within the South African higher educational system in that, unique a course in mechanical engineering was developed to suit AM technology within the South African context and this creates an opportunity to develop a multi-disciplinary research that evolved the manufacturing systems and enhance the academic status of the university.

Some recent research activities of AM at the CUT through the CRPM are presented as follows. Between 2014 and 2015, CUT worked closely with Doctors at the Kimberley Hospital in Northern Cape province of SA and conducted medical procedures involving 3D printing on 12 patients, two of the patients has 3D-printed titanium jaw implants inserted (Helsel, 2015). Another research activity involved a teenage boy born without ear canals at age two; had 60% hearing ability with difficulties trying to communicate. He received two ears at the Groote Schuur hospital with the assistant of CRPM and Fuchs foundation, this was achieved using 3D printing technology, the two ears were designed and manufactured with a positioning device which assists to place the prosthetic implants and the external prosthesis. The CT scan of the patient was converted to create a 3D model which was used to plan the exact position of the auricular implants that held the external prothesis as shown in figure 6a. A 3D printed positioning device was used to the implants, and within 3 months of healing period, the implants were shown to place the prosthetic ears, and impressions was used to cast silicone prosthetic ears that matches the patient's skin tone/colour (CRPM, 2017b).

Recently, Materialise (an active company in the field of AM) donated grant to CRPM to assist some patients with life-changing interventions and also to introduce students to the different benefits of 3D printing technology in the medical field. The grant allowed CRPM to assist a 32 years old woman suffering from "Ossifying Fibroma Tumor" in her lower jaw. The surgical medical team decided to resect the tumor immediately and to place a custom-made laser-sintered titanium implant in the mouth of the patient (Benoit, 2016). The CT scans of the patient was converted to a 3D model, and the resulting 3D model of the bone and tumor was used as input to plan the resection planes and design.

The implant was fitted perfectly, and the models were printed in plastic as seen in figure 5b, the implant itself was 3D printed in titanium. The surgery was successfully carried out through cutting edge guides (Benoit, 2016). A USB with crank action was designed and printed through the CRPM industrial EOSINT P machine and was completely assemble as seen in figure 5c (CRPM-Facebook, 2016). A Titanium prosthetic limb was designed, and 3D printed at CRPM in 2017, and the Titanium prosthetic was also showcased during the annual RAPDASA conference in November 2017 and seen in figure 5d. Another case of myxoma of the midface of a patient having a low quality of life due rapid growth of the effect of the myxoma of the midface, the medical data of the patient was used to produce a plastic/nylon model 1:1 of the patient, the medical team were able to see the actual extent of the defect of the myxoma as shown in figure 5(e) and 5(f), the implant was designed and manufactured using AM technology specifically for the patient, and the operation was successful.

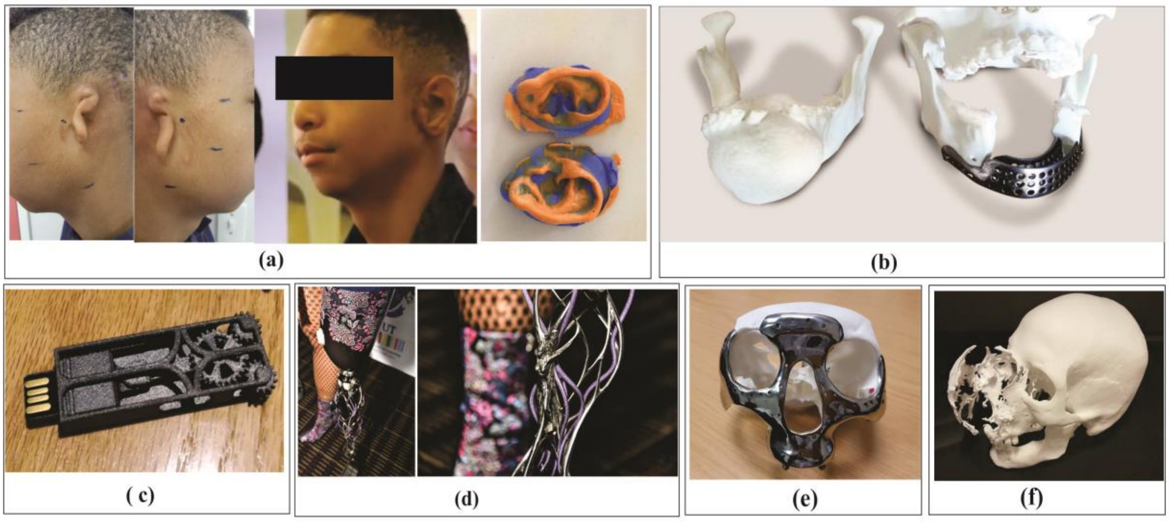

Figure 5: Samples of recent AM technology research at the CUT CRPM Centre. (a) a case of a teenager born without ear canals and received new two ears; (b) 3D model's 3D printed for a 32 years old woman suffering from "Ossifying Fibroma Tumor"; (c) a USB 3D printed and assembled at CRPM; (d) a 3D printed Titanium prosthetic limb for a patient; (e) a Maxilla implant 3D printed using Titanium for a patient; (f) Myxoma of the midface of a patient 3D printed (CRPM, 2017a).

5.2 The Vaal University of Technology

VUT is a university of technology located at the Vanderbijlpark of South Africa. The university has a technology station where excellent AM research activities are carried out. The VUT's science and technology park at the Sebokeng campus has world-class in-house industrial grade AM facilities for commercial, education and research purposes. The AM facilities at the VUT functions as a service bureau that supports local industry and entrepreneurs; and offers research support to both local and international researchers (De Beer, 2010). As at November 2017, the VUT at Sabokeng campus have more than 10 high-end industrial grade AM machines such as (EOSINT P 380, EOSINT P395, FORMIGA P 100, FORMIGA P 110, Voxeljet VX 1000, Voxeljet VX 500, etc.). The Idea 2 Product (I2P)® Lab concept was founded and implemented in 2011 by a team of researchers at the VUT. The aim of Idea 2 Product lab is to serve as platform to transfer technology and innovation of emerging advanced manufacturing technologies such as AM between academic institution and industry.

Currently, VUT offers the highest resolution polymer laser sintering and the AM facilities at VUT uses different AM technologies such as (Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), 3D Printing (3DP), etc.) to manufacture prototypes and products from different AM machines. The VUT AM unit are being funded by Technology Innovation Agency (TIA). As part of VUT plan to introduce AM Education, the Idea to Product (I2P) Lab was established in 2011 to serve as a platform to introduce students to innovative technology using entry-level FDM 3D printers (i.e. UP Mini 3D Printers). The I2P is used to train and introduce students from high schools within the Sebokeng communities to acquire fundamental knowledge of AM technology. Annually, the VUT AM unit usually organizes a program called "*Engineering Week*" to create awareness to high school students by showcasing the benefits of AM technology to students through their world-class in-house AM facilities. Based on the primary data collected, between July 2016 and July 2017, 200 people were trained and introduced to the fundamental AM technologies using the entry-level FDM 3D printers at the I2P lab. The gender of the people trained during this period consists of 90 males and 110 females. The students were first introduced to the fundamental AM technologies such as AM processes, AM product development cycle, design techniques using 123D Autodesk beta software and later the students were exposed to the practical aspect of AM/3D printing technologies where students can convert his/her creative thinking into physical final product using the AM in-house facilities at the AM.

The AM facilities at the VUT is serving the industrial sector (manufacturing, aerospace, etc.) through daily production of 3D printed components. More so, in 2017, almost 30 intern students were admitted at VUT AM unit for one-year internship program with the aim to expose the interns to AM technologies and education and to gain quality knowledge of AM processes and hands-on experience on both entry-level 3D printers and high-end AM machines. According to Campbell and De Beer (2017) since the inception of Idea 2 Product lab at VUT approximately 7500 students have attended I2P lab. Although, the number of students that have attended the I2P lab have increase from 7500 since appropriately 200 students were also trained in 2017. The industrial engineering, and operation management undergraduate students used the I2P lab for Production Engineering IV course in first semester of their degree (Campbell and De Beer, 2017). Also, some lecturers and students in the department of Visul arts and design (specifically, Fine Arts option) used the 3D printing facilities at I2P lab for their final design printing.

5.3 The North-West University

NWU is a university situated on the North-West Province of South Africa and recently, the NWU created an "Additive Manufacturing Research Group" within the Faculty of Engineering and various AM research activities are being carried out. The 3D printing lab at the NWU is being called "NWU Pukke 3D Printing centre" which is equipped with several entry-level FDM desktop 3D printing machines and there are few of UP Mini 3D printing machines at some lecturer's offices on campus for student use as well. The NWU 3D printing centre also has a high-end industrial grade AM machines at the university's fabrication laboratory (FABLAB) for use of the students and academics for design of prototypes, research and development purposes. As part of the recent development in the School of Mechanical Engineering, mechanical engineering students have been encouraged to make prosthetics as part of their final year project and the prosthetic limbs can be offered to patients. The main aim of the project is to assist people for whom the arm or leg has been amputated and could not afford a prosthetic arm, limbs or leg due to a lack of funds (NWU, 2017). In 2017, a master's student at the School of Mechanical Engineering is working on a design of a prosthetic arm for a particular patient and aiming to build a new plastic arm with the 3D printer at the University FabLab (NWU, 2017). Currently, as part of the plan to gradually integrate AM technology into the educational system, the undergraduate students within the mechanical engineering, industrial engineering and electrical and electronic engineering are using the 3D printing centre at the campus to carry out design assignment and unique project related to design and manufacturing.

AM research activities at NWU is gradually expanding as a Doctoral student at Occupational Hygiene unit of the university is working on a research title 'The hazardous chemical substance exposure associated with additive manufacturing processes', and the research is expected to identify the health risks associated with all the manufacturing processes located at the CSIR, VUT, CUT and SU. More so, another Doctoral student in development and management engineering working a research title 'Framework for effective additive manufacturing education at South African universities' and the aim of this research is to develop a framework for AM education using selected SA universities as the case study. Furthermore, two lecturers from School of Mechanical Engineering working on a research project titled "Additive Manufacturing Material Characterization" with the aim to determine the material properties of various EDM materials which are usually used in 3D printing. Figure 6 shows a collage of some of the 3D printed components designed and manufactured by the engineering students.

Figure 6: The collage of some of the final 3D printed products designed by the engineering students using the NWU Pukke 3D printing centre.

5.4 Stellenbosch University

The Stellenbosch University (SU) is a research-intensive university located in the town of Stellenbosch, South Africa. Over the years, SU has involved in various AM research activities, most especially within the industrial engineering department; and the resource efficiency engineering management research group. The university has a Rapid Product Development Laboratory (RPDLab). The RPDLab is leading the SU effort to explore 3D printing's value in manufacturing, prototyping, architecture and medicine. SU students have used AM machine to make models of products like "cell phones, remote controls, underwater cameras, corkscrews, elaborate perfume models, innovative electrical plugs and the Eiffel Tower" (Dimitrov, 2006). The university's medical school is also using 3D printing through the conversion of CT and MRI scans data into 3D models for both academic and clinical purposes, and this enables the students to examine anatomy without surgery or dissection and to practice and plan skill-intensive procedures and treatments which is helpful for visualizing abnormalities such as tumors and birth defects (Dimitrov, 2006). The work at the RPDLab exposes several students across multiple disciplines to AM technologies, not only engineering students. Dimitrov (2006) stresses that the scope of possible uses for AM across the universities is only broadening as additional educational opportunities are uncovered. The importance of AM education at SU combines students' involvement with industry partnership and high-end AM technology equipment, which provide university-industry collaboration in AM technology research. In short, this has provided unprecedented education potential for Stellenbosch University students by gain hands-on-experience while working with industry-partners (Dimitrov, 2006).

AM research and development at the SU is on small-scale compared to other universities like CUT and VUT that have quite several high-end industrial grade AM machines. As part of the mission of SU to promote AM technology within the university system, an Idea 2 Product Lab was established in 2015 for manufacturing of on-demand 3D print components. The AM in-house facilities at the SU aimed to bring AM technology to everyone (for instance, students, academic staffs and the general public) by making it accessible and easy to learn for those new to the technology (I2PLab, 2017). The Idea 2 Product is an open access for self-use CAD and 3D printing which allows class group to incorporating AM into courses at the university. The I2P lab in-house facilities comprises of 3D printing machines and 4 entry-level desktop 3D printers and 3D Scanner which is accessible to students for design project purposes as shown in figure 7a and figure 7b shows some samples of 3D printed parts at the SU's I2P lab.

(a)

(b)

Figure 7: Samples of finished 3D printed components and the AM in-house facilities at the I2P lab at SU. (a) a collage that shows some samples of 3D printed components (b) some of the 3D printers and 3D scanner facilities

6. Sustainability of Additive Manufacturing from Education Perspective

The term "sustainability is a varied conception in today's world and the concept of sustainability was largely motivated as a result of a series of environmental incidents and disasters, fears from chemical contamination and resource depletion" (Malshe *et al* 2015). In 2013, a workshop was organized by the United States National Science Foundation (NSF) and the workshop was titled: *Frontiers of Additive Manufacturing Research and Education.* Different stakeholders from the academics, industries and governments were present at the workshop. . The stakeholders shared their ideas, innovations and knowledge as relating to the frontiers of AM education, research and technology transfer (Huang and Leu, 2014). The report from the workshop summarizes the current state, future potential gaps and needs for AM education with appropriate recommendations.

AM education and training are rapidly growing worldwide; most especially in the US. The technology is playing a significant role in promoting and establishing a healthy engineering education ecosystem in colleges and universities (Huang and Leu, 2014). Some of the crucial ways to further promote AM education and its sustainability was identified by NSF during the workshop as stated below (Huang and Leu, 2014):

- University-industry collaboration,
- Technology transfer,
- Education and training, and
- Technology and research

To sustain AM education, some barriers to AM education need to be addressed, such lack of AM educational practitioners, cultural differences, acceptability of AM technology in the universities, colleges and industries, vested interests and lack of imagination and innovation. Bourell *et al* (2009) made certain recommendations to overcome AM education limitations as follows:

- Prolong university courses on additive manufacturing,
- Provision of education materials,
- Creation of curriculum at technical colleges, undergraduate and postgraduate levels and
- Training program in additive manufacturing for industry practitioners with certification.

7. The SWOT Analysis

A SWOT analysis is a tool used to analyse the strengths, weaknesses, opportunity and threats in businesses, organization and research. SWOT analysis can be referred as a framework to assist the researchers to identify and prioritize research goals and can be used to further pinpoint the strategies of achieving the set goals (Ommani, 2011). The strengths and weaknesses are referred to as internal factors while the opportunities and threats as the external factors. In this paper, SWOT analysis is used to evaluate the present and future prospects of AM education and research at SA universities.

Table 1: The SWOT analysis to evaluate present and future prospects of AM education and research.

Strengths (S)	Weakness (W)
The availability of high-end AM machines at selected SA universities is a major advantage in promoting AM education and research in area such as aerospace, medical, automobile and industrial designs. Establishment of more 12P lab at SA high schools, colleges and universities will enhance innovative and creative thinking among students and develop interest in STEM education. In the coming years, RAPDASA will serve as the right vehicles to promote AM activities in SA through the annual international conference and to create global awareness. Over the years, Technology Transfer has played a major role in advancing AM technology at SA universities and will continue to play an important role by providing both theoretical and practical knowledge to students, academia, entrepreneurs and professionals in SA.	To effectively promote AM education, there is a need for SA government through DST to create more centre of excellent in of AM and Research Chair in AM at selected universities. SA AM strategy aimed to create an enabling capability development environment for AM technology and promote AM education at all levels, e.g. colleges and universities. To achieve this aim, more AM in-house facilities needed at SA's universities. To encourage more postgraduate students and young researchers to attend annual RAPDASA conference and to get expose to AM technology and research. RAPDASA conference committee should increase their scholarship to allow more people to attend. More AM technology awareness need to be done at SA Higher Education Institutions (HEIs) in order to increase AM professionals/experts because insufficient AM personnel/educator is one of the factors identified limiting the advancement of the technology in SA.
Opportunities	**Threats**
An introduction of a postgraduate degree, for example "MSc or MEng" program in AM at major SA universities. This will serve as opportunities to increase the number of professionals and expertise in the field of AM in SA. Availability of large amount of Titanium in SA creates a great opportunity for production of medical implant and titanium prosthetic. Likewise, SA platinum powder will enhance the jewellery industry in SA using AM technology. Efficient University-Industry collaboration would enhance AM research activities at the university and expose students and academic to AM education. Such collaboration can attract more internship for students, and funding for the universities to conduct research in emerging areas of AM technology. CUT indicated that a course in mechanical engineering was introduced to suit AM technology within the SA context. To enhance AM technology growth among students at SA universities; an inclusion of a course or some topics in manufacturing courses related to AM in the undergraduate curriculum at the universities will serve a good platform to educate people about AM technology and promote a career path in AM field.	High cost of AM system and the materials, most especially the high-end industrial AM machines is a threat to many HEIs and industries and it is delaying the adoption of AM technology. Lack of effective framework for AM education for SA universities is another threat that need to be addressed in the future. For more quality and advanced research in AM, consistent funding from NRF/DST and other funding bodies is needed, for SA AM research to compete globally in cutting edge research.

8. Conclusion

This paper presents comprehensive AM research activities within the selected SA universities, thereby promoting AM education. The paper presents an up-to-date history of AM in South Africa and the SA AM strategy. This paper focuses on AM education and presents the global perspective of AM education, and sustainability of AM education. One of the limitations this paper is that, the scope was limited to AM activities at South Africa universities and does not present the application of AM/3D printing in education. For SA government to fully reap the enormous benefits and huge investment they have put in AM technology, there is a need for more research activities at SA universities. It is believed that various AM research activities across the major universities and colleges would serve a platform to introduce AM education in SA. Recently, an initiative has initiated to develop an AM course or curriculum for teaching AM at the South African universities. However, within the Higher Education Institutes in South Africa, students are being exposed to AM education through courses related to design and manufacturing especially within the engineering degree using the AM in-house facilities at the I2P lab or AM/3D printing centre. More so, the lead author of this recommend the inclusion of a full or short semester course in AM at the SAs' universities which would serve as another great milestone for SA AM industry; as well as introduction of a postgraduate program (i.e. master's degree) in AM to increase AM research at the universities. An effective AM education and research at the universities the will make many students to develop interest in AM/3D printing technology and pursue career path in additive manufacturing.

References

Benoit, S. (2016). 3D-Printed Custom Implant Helps Patient with Ossifying Fibroma. http://www.materialise.com/en/blog/3d-printed-custom-implant-helps-patient-ossifying-fibroma#more-6180. Date of access: 13 Dec. 2017.

Bourell, D., Leu, M. and Rosen, D. (2009). Roadmap for Additive Manufacturing—Identifying the Future of Freeform Processing. The University of Texas: Austin.

Briggs, S. (2014). How 3-D Printing Will Change Education. InformED. http://www.opencolleges.edu.au/informed/features/how-3-d-printing-will-change-education/. Date of access: 29 Nov. 2017.

Campbell, R.I., & De Beer, D.J. (2005). Rapid prototyping in South Africa: past, present and future. Rapid Prototyping Journal. 11(4): 260 – 265.

Campbell, R.I., de Beer, D.J. and Pei, E. (2011). Additive manufacturing in South Africa: building on the foundations. *Rapid Prototyping Journal*, 17 (2), pp. 156 – 162.

Campbell, R. I. and De Beer, D. J. (2017). Using-Idea 2-Product Labs as a Strategy for Accelerating Technology Transfer. International Journal of Technology Transfer and Commercialisation, 14(2): 249-261.

CRPM-Facebook. (2016). CRPM Equipment. On their Facebook page. https://web.facebook.com/pg/CRPMISO/photos/?tab=album&album_id=319367695065826. Date of access: 08 Dec. 2017.

CRPM. (Centre for Rapid Prototyping and Manufacturing). 2017a. http://www.crpm.co.za/. Date of access: 08 Dec. 2017.

CRPM. (2017b). Medical Prosthesis. http://www.crpm.co.za/project/medical-prosthesis/.

CSU (Colorado State University). 2016. MECH 502 - Advanced/Additive Manufacturing Engineering. www.online.colostate.edu/global/docs/syllabi/MECH502.pdf. Date of access: 28 Nov. 2017.

De Beer, D. J. (2010). Additive manufacturing as tool to support sustainable development. *Annals of DAAAM for 2010 & Proceedings for the 21st International DAAAM symposium. Academic Journal.* 21(1).

De Beer, D.J. (2011). Establishment of rapid prototyping/additive manufacturing in South Africa. Journal of the South African Institute of Mining and Metallurgy, 111(3):211-215.

De Beer, D. J., and Du Preez, W.B. (2015a). Implementing the South Africa additive manufacturing technology roadmap – The role of an Additive Manufacturing Centre of Competence. *South African Journal of Industrial Engineering.*26(2):85-92.

De Beer, D, J. (2015b). South African Additive Manufacturing Landscape/Growth of 3D Printers, 1991-2015. Figure Supplied by Prof Deon de Beer.

Despeisse, M. and Minshall, T. H. (2017). Skills and Education for Additive Manufacturing: A Review of Emerging Issues. APMS 2017: Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, 513: 289-297.

Dickens, P., Reeves, P. and Hague, R. (2012). Additive Manufacturing Education in the UK. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-01-Dickens.pdf.

Dickens, P., Reeves, P. and Hague, R. (2016). Additive Manufacturing Education in the UK. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-01-Dickens.pdf.

Dimitrov, D., Schreve, K., & De Beer, N. (2006). Advances in Three-Dimensional Printing - State of the Art and Future Perspectives. *Rapid Prototyping Journal*, 12(3), 136-147.

Dimitrov, D. (2006), "Stellenbosch University, Department of Industrial Engineering proves the value of 3D printing in manufacturing, architecture, and education", 3d Rapid Prototyping Case Studies: Stellenbosch University. http://www.3dsystems.com/learning-center/case-studies/stellenbosch-university-department-industrial-engineering-proves-value. Date of access: 01 Dec. 2017.

Dimitrov, D.M. & De Beer, N. (2014). Improvements in the capability profile of 3-D printing: An update. *South African Journal of Industrial Engineering.*25 (2): 1-12.

Drakoulaki, A. (2017). 3D printing as Learning Activity in Higher Education: A case study in a robotics' prototyping course. Oslo: University of Oslo. [UiO: Master – Dissertation].

Du Preez, W. B and de Beer, D. J. (2006). RAPDASA–A vehicle for product development technology diffusion in South Africa. Doc No: CSIR/MSM/MMP/EXP/2006/0082/A.

Du Preez, W., De Beer, D., Greyling, H., Prinsloo, F., Sciammarella, F., Trollip, N., Vermeulen, M. and Wohlers, T. (2016). A South African Additive Manufacturing Strategy. Department of Science and Technology.

Go, J. and Hart, AJ. (2015). A framework for teaching the fundamental of additive manufacturing and enabling rapid innovation. Department of Mechanical Engineering and Laboratory for Manufacturing and Productivity Massachusetts Institute of Technology, Cambridge, MA.

Hague, R., Reeve, P. and Jones, S. (2016). Additive manufacturing: mapping UK research into 3D printing. https://www.gov.uk/government/publications/additive-manufacturing-mapping-uk-research-into-3d-printing. Date of access: 01 Dec. 2017.

Helsel, S. (2015). South Africa's Central University of Technology Awarded Grant for 3D Printing Research. https://inside3dprinting.com/news/south-africas-central-university-of-technology-awarded-chair-in-medicine-grant-for-3d-printing-research/33433/. Date of access: 08 Dec. 2017.

Huang, Y. and Leu, M. C. (2014). Frontiers of Additive Manufacturing Research and Education. Center for Manufacturing Innovation. Florida: University of Florida.

Huston, D., Van Epps, A., Sherrill, J., Alvar, A. and Bowen, A. (2015). How 3D Printers Support Teaching in Engineering, Technology and Beyond. https://www.asist.org/publications/bulletin/oct-15/how-3d-printers-support-teaching/. Date of access: 01 Dec. 2017.

QTR (Quadrennial Technology Review). 2015. Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. Additive Manufacturing Technology Assessment. US Department of Energy.

ITEEA. (2016). 2016 National Forum on Additive Manufacturing Education and Training. https://www.iteea.org/News/282/102342.aspx. Date of access: 03 May 2017.

I2PLab. (2017). Idea2Product Lab Stellenbosch. 3D printing facility - low cost, easy access. blogs.sun.ac.za/idea2product/about_prices/. Date of access: 13 Dec. 2017.

Jordaan, G. D. 2010. A Business Model for Rapid Prototyping in South Africa. *Academic Journal*. Annals of DAAAM & Proceedings; 2010, p1561. http://www.freepatentsonline.com/article/Annals-DAAAM-Proceedings/246014346.html.

Jordaan, J. (2017). Technology and Innovation. http://www.cut.ac.za/technology-innovation/. Date of access: 08 Dec. 2017.

Koslow, T. (2016). South Africa's 3D Printing Sector Shows Potential Growth Across the Board. https://3dprint.com/147991/south-africa-3d-printing/. Date of access: 03 Dec. 2017.

Kunniger, D. (2015). Diffusion of additive manufacturing in Gauteng South Africa. Pretoria: University of Pretoria. (Dissertation – Masters).

Lin, F., Zhang, L., Zhang, R. and Zhang, T. (2012). Innovative education in additive manufacturing in China. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-02-Lin.pdf.

Loughborough. (2018). (Loughborough University). Design for Additive Manufacturing. MSc Program. http://www.lboro.ac.uk/study/postgraduate/masters-degrees/a-z/design-additive-manufacture/. Date of access: 10 Oct. 2018.

Martin, A. (2013). Exciting Developments in Uses of 3D Printing in Education. http://www.emergingedtech.com/2013/05/exciting-developments-in-uses-of-3d-printing-in-education/. Date of access: 29 Nov. 2017.

Malshe, H., Nagarajan, H., Pan., Y. and Haapala, K. (2015). Profile of sustainability in additive manufacturing and environmental assessment of a novel stereolithography process. ASME. International manufacturing science and engineering conference. Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing, Vol. 2.

MicroFabricator. (2017). South Africa’s government invests R17 million in metal 3D printing startup. http://microfabricator.com/articles/view/id/58ee5df43d2d2eca1d8b4567/south-africa-s-government-invests-r17-million-in-metal-3d-printing-startup#. Date of access: 30 Nov. 2017.

Minetola, P., Luliano, L., Bassoli, E. and Gatto, A. (2015). Impact of additive manufacturing on engineering education - evidence from Italy. *Rapid Prototyping Journal, Emerald Group Publishing Ltd*., 25(5):535-555.

NSTF (National Science and Technology forum). 2016. Discussion Forum S.E.T for Socio-Economic Growth. Light-based Technologies Innovation Forum - Advances in light-based technologies in solar energy, additive manufacturing and fibre optic communications. http://www.nstf.org.za/discussion-forum/light-based-technologies-innovation-forum/. Date of access: 30 Nov. 2017.

NWU. 2017. (North West University-News). NWU wants to manufacture affordable artificial limbs. http://news.nwu.ac.za/nwu-wants-manufacture-affordable-artificial-limbs. Date of access: 30 Nov. 2017.

Oberholzer, E. (2018). Aeroswift: The biggest, state-of-the-art 3D Printer in SA. https://www.thesouthafrican.com/aeroswift-biggest-3d-printer/. Date of access: 05 August 2018.

Ommani, A. R. (2011). Strengths, weaknesses, opportunities and threats (SWOT) analysis for farming system businesses management: Case of wheat farmers of Shadervan District, Shoushtar Township, Iran. *African Journal of Business Management*, 5(22): 9448-9454.

Optics. (Optics.org) 2017. GE investing $10m in additive manufacturing education. http://optics.org/news/8/1/14. Date of access: 02 May 2017.

Pennstate. (2017). Penn State to offer new additive manufacturing and design graduate degrees. http://www.ime.psu.edu/news/amd-degrees-sp17.aspx. Date of access: 02 May 2017.

Platt, J. R. (2015). Thirty-five percent of engineering jobs now require 3-D printing skills. http://theinstitute.ieee.org/career-and-education/career-guidance/thirtyfive-percent-of-engineering-jobs-now-require-3d-printing-skills. Date of access: 01 Dec. 2017.

PRNewswire. (2017). UL and Ricoh announce Training Collaboration to focus on Additive Manufacturing education. http://www.prnewswire.com/news-releases/ul-and-ricoh-announce-training-collaboration-to-focus-on-additive-manufacturing-education-300402470.html. Date of access: 02 May 2017.

Radharamanan, R. (2017). Additive Manufacturing in Manufacturing Education: New Course Development and Implementation. *American Society for Engineering Education, ASEE Annual Conference and Exposition paper.* pp1-14. Paper ID #20377.

Scott, C. (2017a). Collaboration Leads to South Africa's First Platinum 3D Print. https://3dprint.com/194222/south-africa-platinum-3d-print/. Date of access: 03 Dec. 2017.

Scott, C. (2017b). South Africa’s Giant Aeroswift 3D Printer Gearing Up for Commercial Production. **https://3dprint.com/166672/south-africa-aeroswift-project/**. Date of access: 05 August 2018.

Sculpteo. (2015). 3D Printing in education: from eLearning to eMaking. https://www.sculpteo.com/blog/2015/11/17/3d-printing-in-education-from-elearning-to-emaking/. Date of access: 29 Nov. 2017.

UOS (University of Sheffield). 2016. MSc (Res) Additive Manufacturing and Advanced Manufacturing Technologies. www.sheffield.ac.uk/mecheng/prospectivemsc/additive-manufacturing University of Sheffield. Date of access: 08 Nov. 2016.

VUT (2017). Technology Transfer and Innovation. http://www.vut.ac.za/about-tti/. Date of access: 14 Dec. 2017.

Waseem, K., Kazmi, H. A. and Qureshi, O. H. (2016). Innovation in Education - Inclusion of 3D-Printing Technology in Modern Education System of Pakistan: Case from Pakistani Educational Institutes. *Journal of Education and Practice*, 7(36): 1-8. ISSN 2222-1735.

Wild, S. (2013). Titanium project has global impact. https://mg.co.za/article/2013-06-07-00-titanium-project-has-global-impact. Date of access: 30 January 2018.

Wild, S. (2014). South African companies take to 3D printing. http://www.mediaclubsouthafrica.com/tech/4026-south-african-companies-take-to-3d-printing. Date of access: 16 Dec. 2017.

Williams, C. B. and Seepersad, C. C. (2012). Design for additive manufacturing curriculum: A problem- and project-based approach. In *23rd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF*:81-92. (pp. 81-92). University of Texas at Austin. [Astract].

Williams, G. (2016). Additive manufacturing has huge potential in South Africa. http://www.bdlive.co.za/business/management/2016/08/31/additive-manufacturing-has-huge-potential-in-sa. Date of access: 16 Dec. 2017.

Wohlers, T. (2004). Additive Manufacturing Report, *Wohlers Annual Worldwide Progress Report,* Wohlers Associates.

Wohlers, T. (2016). 3D printing, additive manufacturing and manufacturing review. http://wohlersassociates.com/blog/category/additive-manufacturing/page/2/. Date of access: 30 Nov. 2017.

Zelinski, P. (2016). Educators and Industry Discuss Need for Engineering Education to Adapt to AM. http://www.additivemanufacturing.media/blog/post/educators-and-industry-discuss-need-for-engineering-education-to-adapt-to-am. Date of access: 01 Dec. 2017.

Appendix G

Entry-Level FDM 3D Printers as a Tool for Additive Manufacturing Education using Idea 2 Product (I2P) ® Lab Concept

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Abstract

The 3D printing technology is a process of creating a physical object from 3-dimensional digital model layer upon layer. 3D printing is also known as Additive Manufacturing (AM) and forms part of a group of identified emerging or disruptive technologies of the 21st century. In recent times, AM education gained much attention both within the academic and manufacturing industries. The cost of high-end industrial AM machines is very expensive, and most universities and colleges across the globe cannot afford this sophisticated AM platforms in their laboratories. This makes it difficult to introduce AM education within their educational programmes. However, the entry-level FDM 3D printers are getting more affordable across the world. Entry-level 3D printers have been identified suitable for the educational environment and serve as a tool to introduce AM into the classroom. The Idea 2 Product (I2P) ® lab concept was established as a self-help laboratory for product development and innovation at the Vaal University of Technology (VUT) as amongst others, a platform for AM education. This paper presents the potential of entry level FDM 3D printers as tool for AM education at all educational levels, using the VUT's Idea 2 Product (I2P) ® Lab concept as a case study.

Keywords: Additive Manufacturing Education, Additive Manufacturing, 3D printing, Entry-Level FDM 3D Printers, Idea 2 product Lab.

1. Introduction

The 3D printing technology is a process of creating a physical object from 3-dimensional digital data, layer upon layer; and it is also known as Additive Manufacturing (AM). The technology has been identified as an emerging and disruptive advanced manufacturing technology of the 21st century and forms part of the technologies included in a group of enabling technologies, collectively referred to as the Fourth Industrial Revolution (FIR) or Industry 4.0. Additive manufacturing technology is an exciting development in the educational sector across the world. The novelty of the technology is rapidly revolutionizing colleges, universities, and schools; and bringing great possibilities to different educational disciplines ranging from Science, Technology, Engineering, Mathematics (STEM); and as well as Geography, Geology, Biology, Chemistry, Design and Fine Arts, etc. (Schelly *et al*, 2015).

The wide-spreading of entry-level FDM 3D printers and recent development of more user-friendly, low-cost (or free) Computer Aided Design (CAD) software for tablets used by young children is enhancing the education of people to AM/3D printing technologies from a social, economic and environmental perspective (Huang *et al,* 2013, Wittbrodt *et al,* 2013 and Minetola *et al,* 2015). The entry-level FDM 3D printing machines are also referred to as Desktop 3D printers, for example UP Mini 3D printers (De Beer. 2015). The use of entry-level FDM 3D printing technology in the Idea 2 Product lab is an initiative that breaks the norm to find educational solutions from a simple idea to more complex products and provides near-to-market 3D printed products (Makerstation, 2017). The entry-level FDM 3D printers market has grown at an exponential rate in the last couples of years. Also, the overall use of these machines within the educational sector have greatly improved both in performance and efficiency. This helps students to gain both educational and industrial skills, and the experience needed to take up related jobs in the AM field (Lotz, *et al,* 2013).

For instance, different manufacturers of entry-level FDM 3D printers have emerged and brought a tremendous increase in the number of entry-level FDM 3D printers in South Africa. The AM systems and 3D printing technologies, especially the desktop 3D printing machines in South Africa have grown rapidly between 1994 and 2015 (Campbell and De Beer, 2005; Campbell *et al*, 2011; De Beer, 2011). The number of AM machines have grown from 32 to 3500 as documented by De Beer in 2015, as shown in figure 1. Out of the 3500 AM machines recorded between 1994 and 2015, 85% of the AM machines were entry-level FDM 3D printers and 15% are advanced AM machines.

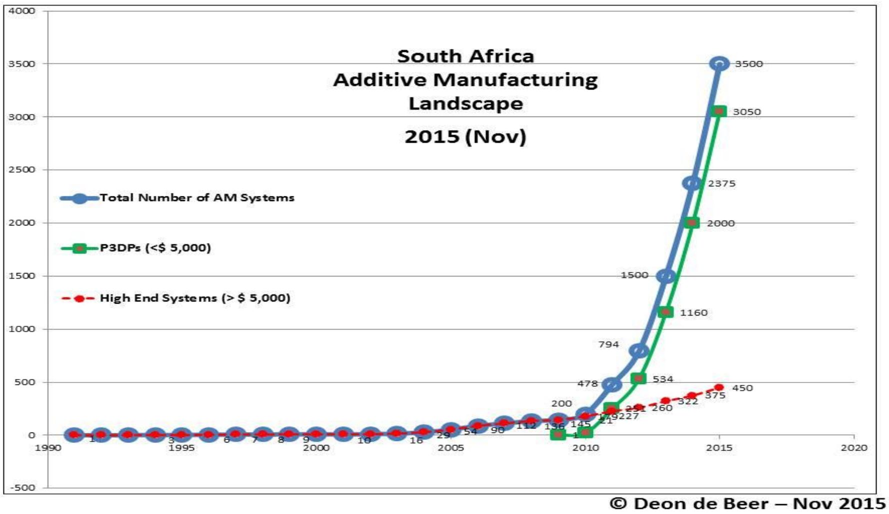


Figure 1: South African Additive Manufacturing Landscape/Growth of 3D Printers, 1991-2015 (Supplied by: De Beer: 2015).

Entry-level FDM 3D printing technologies introduce students to AM education at all levels, promote innovative and creative thinking; and provide the opportunity to students to experience the model stage of the design process while improving their problem-solving skills (Lacey, 2010; Schelly *et al*, 2015). Lacey (2011) explains that "projects that involve 3D printing facilitate learning in an immersive, fun manner, encouraging students' personal investment in their Science, Mathematics and Engineering coursework" (McNally, 2011).

The lead-author of this paper spent approximately three months at the AM unit of the Vaal University of Technology (VUT), Science and Technology Park, Sebokeng campus to gain necessary hands-on-experience of both entry-level FDM 3D printers and high-end additive manufacturing machines. The center is being funded amongst others by the Technology Innovation Agency (TIA). During this study the impact and applications of AM technology within the educational system have been identified, especially within the engineering degree. The VUT Science and Technology Park, Sebokeng campus comprises of seven units, namely: TTI (Technology Transfer and Innovation), TS (Technology Station), EDU (Enterprise Development Unit), EMC (Engineering Manufacturing Centre), ICBT (Institute of Chemical and Bio-Technology), IIC (Iscor Innovation Centre) and Idea to Product (I2P) Laboratory (VUT, 2017). In this paper, emphasis will be on the Technology Transfer Innovation (TTI) unit, the additive manufacturing and Idea 2 Product (I2P) Lab unit.

This paper introduces entry-level FDM 3D printing technologies; presents some evidence and benefits of entry-level FDM 3D Printers within the educational sector; briefly describes the Idea 2 Product (I2P) ® Lab concept at the VUT; presents the growth and spreading of Idea 2 Product (I2P) ® Lab concept from a global perspective; and presents two case studies to show that entry-level FDM 3D printing technology is a tool for AM education using the Idea 2 Product (I2P) ® Lab concept.

2. Additive Manufacturing Technologies for Entry-Level 3D Printing

Amongst others, AM technology comprises of liquid-based and powder-based technologies. The powder-based technologies are Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). The liquid-based technologies include Stereolithography (SLA/SL), Digital Light Processing (DLP), etc. Fused Deposition Modelling (FDM) is also known as Fused Filament Fabrication (FFF) is widely used and belongs to material extrusion family. The FDM was invented in the late 1980s by Scott Crump, a co-founder and past chairman of Stratasys Ltd; and Stratasys is a global leading manufacturer of AM systems/3D printers. The Laminated Object Manufacturing (LOM) belongs to sheet lamination family and was developed in 1991 by Helisys Inc.; a California based company, now (Cubic Technologies). Most of today's entry-level desktop 3D printers uses FDM technology that heated plastic to its melting point and thereafter extruded it layer upon layer to produce a 3D printed final part. However, some entry-level FDM 3D printers use the LOM technology (Palermo, 2013).

The FDM technology was commercialized fully in 1990 (HS3DP, 2016). Zein *et al* (2002) explained that FDM technology uses a small temperature-controlled extruder to force semi-molten thermoplastic filament material through a nozzle and deposit the semi-molten polymer onto a platform in a layer by layer process. The monofilament is moved by two rollers and acts as a piston to drive the semi-molten extrudate. At the end of each completed layer, the base platform is lowered, and the next layer is deposited. The designed object is fabricated as a three-dimensional part based solely on the precise deposition of thin layers of the extrudate (Zein *et al*, 2002). Amongst others, FDM systems use common thermoplastic materials such as acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), and Polyetherimide (PEI) to print industry grade 3D models. Figure 2 shows a schematic diagram of the FDM operation (CustomPartNet, 2009).

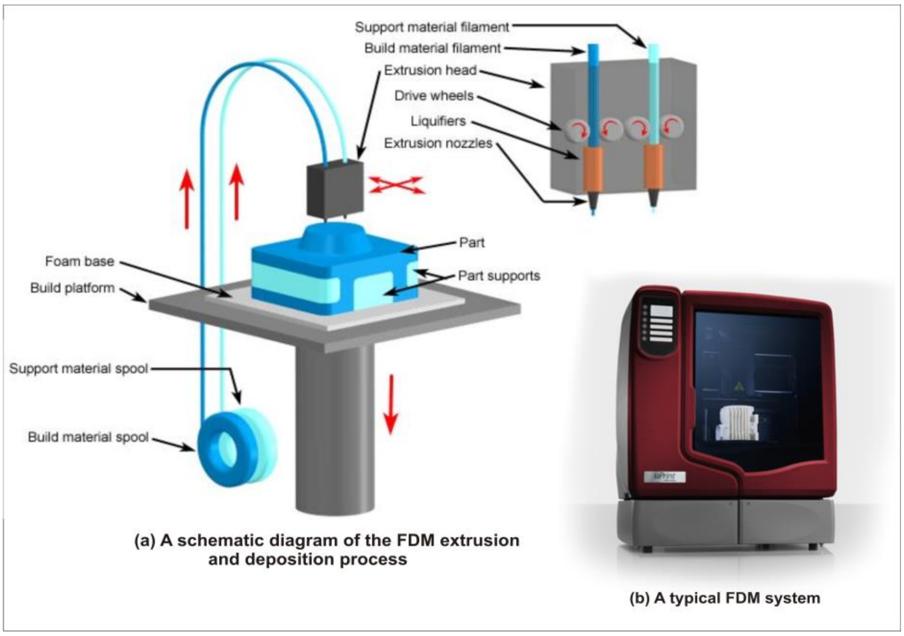


Figure 2: Fused deposition modelling AM technology (CustomPartNet, 2009)

3. The Impact of Entry-Level FDM 3D Printing Technology within the Educational Sector

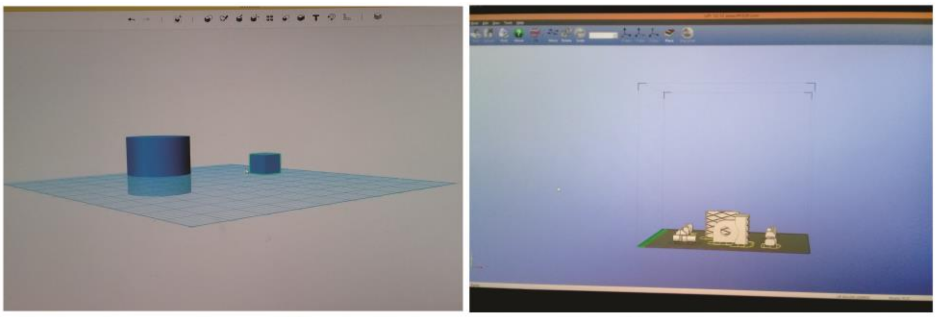
A case study was conducted at an Italian university to investigate the impact of AM on engineering education, that is, to evaluate how the direct access to AM systems could have impact on education of future mechanical engineering student within a master's program (Minetola *et al* 2015). The study used a survey that was specifically designed to access the relevance of entry-level FDM 3D printers within the learning environment as a tool for project development (Minetola *et al* 2015). The findings from the study has shown a positive relationship of access to additive manufacturing systems to perceive interest, motivation and ease of learning of mechanical engineering. Also, the study has proven that entry-level FDM 3D printers provide hands-on experience within the academia and promote extensive acquisition of technical knowledge for mechanical engineering students.

Buehler *et al* (2014) describes the application of AM as a tool for customized learning aids that would assist students with disabilities. Kostakis *et al* (2015) shows the educational use of entry-level FDM 3D printers at two high schools from a Greece perspective based on theoretical framework that involved an experimental education scenario using the 3D design and 3D printing system. The study used a qualitative research approach (i.e. a questionnaire on different aspects). Kostakis *et al* (2015) aimed to examine to what degree the technological capabilities of open source 3D printing and how it could serve as a means of learning and communication. To achieve the aim to the study, 33 students were requested to collaboratively design and make a creative artifacts using an open-source 3D printer and 3D design software. The answers to the questions in the qualitative survey were limited to Yes and No options. The finding showed a "positive arguing that 3d printing and design can electrify various literacies and creative capacities of children in accordance with the spirit of the interconnected, information-based world". Wong *et al* (2014) also carried out some studies at the Additive Manufacturing Innovation Centre (AMIC) at Singapore Nanyang Polytechnic and studies show some applications of AM/3D printing from an educational perspective.

Furthermore, Brett *et al* (2015) examined the implementation of entry-level 3D printers from both small businesses and education; and identified the corresponding benefits, implications and challenges. The study used a questionnaire survey in parallel with an interview-based feedback, which allowed the researchers to develop an understanding of the use of entry-level 3D printing among three businesses. The findings showed that adoption of entry level 3D printing technologies was enabled through hands-on experience. It was stated that entry-level 3D printers serve as a platform to prepare the workforce within small business with the opportunity to eventually work with high-end/industrial grade additive manufacturing systems (Brett *et al*, 2015). Different studies have examined the impact of entry-level FDM 3D printers and these have shown that AM research should not be limited to more advanced industrial grade additive manufacturing systems but both entry-level FDM 3D printing technology and industrial grade additive manufacturing machines (Pei, 2015). Pei (2015) believes that in the future more affordable entry-level 3D printers will be available, especially as teaching of computer aided design CAD and AM education become prevalent in high schools, colleges, and universities.

In South Africa, since the inception of Idea 2 Product Lab at VUT and other universities such as (Stellenbosch University, North-West University, etc.) and other centres across the country, it has shown that the use of entry-level FDM 3D printing technology has great impact on science and engineering students, and it enables the high school learners to develop interest in studies related to Science, Technology, Engineering and Mathematics (STEM). On the VUT campus, entry-level FDM 3D printers in the Idea 2 Product lab are being used by Industrial Engineering students for course work in Production Engineering IV and final year projects. In 2014, it was recorded that the Industrial Engineering and Operation Management students used the entry-level FDM 3D printers in the Idea 2 Product (I2P) lab for their first semester subject in Product Engineering IV and approximately 85 students were involved in the course (De Beer and Campbell, 2017). During this course, the I2P Lab was used, and the students were exposed to product design techniques using the 123D Autodesk beta software and other softwares such as SolidWorks (De Beer and Campbell, 2017).

Currently, some of the students and lecturers in the Department of Fine Art and Design are also using the entry-level FDM 3D printers in the I2P lab for printing their designs. The designs are carried out using related Fine Art Software, which are then converted into STL files and the final products are produced in the Idea 2 Product lab. Figure 3a shows the 123D Autodesk beta software design platform, known as entry-level CAD software. The design software is very useful for the students during the training stage, especially for the beginners in Computer Aided Design and AM technology. Figure 3b also shows the UP mini entry-level FDM 3D printers software that allows the .STL files to be transferred to the 3D printers.



(a) (b)

Figure 3: Show the pictorial representation of (a) the 123D Autodesk beta software (b) the UP mini entry-level FDM 3D printer software

4. Idea 2 Product (I2P) ® Lab at the Vaal University of Technology

The Idea 2 Product (I2P) ® Lab concept was founded and implemented in 2011 by a team of researchers at the VUT. The aim of Idea 2 Product lab is to serve as platform to transfer technology and innovation of emerging advanced manufacturing technologies such as AM between academic institution and industry. Idea 2 Product is recognized as self-help laboratory, fitted with entry-level 3D printing facilities for innovation, education, creative engagement and product development at the VUT, which is purposefully to also empower people and develop the community. In an ideal environment, Idea 2 Product lab enables advanced manufacturing and allows university-industry collaboration (CSU Ventures, 2013). The Idea 2 Product lab uses new found interest converting a CAD drawing into a 3D physical model using small Fused Deposition Modelling (FDM) 3D printers, also known as entry-level FDM 3D Printers. With the use of Idea 2 Product lab, the younger generation of entrepreneurs and students at the university have the privilege to bring their initial ideas, innovations and creativities into tangible 3D products (Havenga, 2017).

The I2P lab provides the students with hand-on experiences and relevant skills enhancement with respect to their initial ideas. Entry-level FDM 3D printers usually uses two types of 3D printing materials, namely, PLA (Polylactic Acid) and ABS (Acrylonitrile Butadiene). Polylactic Acid is a biodegradable thermoplastic aliphatic polyester derived from renewable resources while Acrylonitrile Butadiene Styrene is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The entry-level FDM 3D printers at the I2P lab at VUT includes UP Plus, UP Mini, BFB 3000, BFB touch, and 3D Cube. Each machine has a different maximum print area, and minimum layer thickness ranging from 0.127 mm to 200 microns. For example, the maximum print area for UP Plus 3D printer is 140mm x 140mm x 135mm, while Cube has maximum print area of 140mm x 140mm x 140mm. In addition, the I2P lab have more advanced FDM Machines such as FORTUS 900mc, FORTUS 250mc, FORTUS 400mc and a ZPrinter 850. The AM unit also has some high-end additive manufacturing machines such as EOSINT P 380, EOSINT P395, FORMIGA P 100, FORMIGA P 110, Voxeljet VX 1000, Voxeljet VX 500, etc. Figure 4 shows the entry-level 3D printing technologies facilities at the VUT I2P at the Sebokeng campus; and some samples of recent 3D printed products.

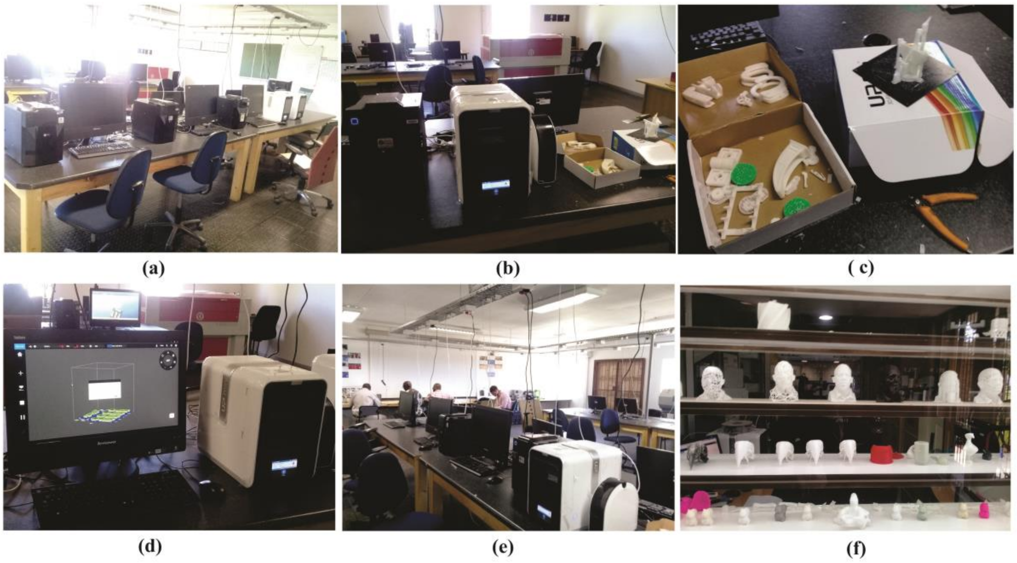


Figure 4: This shows the entry-level 3D printing technologies facilities at the VUT Idea 2 Product lab at the Sebokeng campus. The (a, b, d, e) shows the arrangement of the computer systems and entry-level FDM 3D printers and (c, f) shows samples of the 3D printed parts at I2P lab

Presently, the VUT's Idea 2 Product lab concept provides a new home-grown technology transfer model and through this innovation the members of the institution's community are empowered with fundamental AM knowledge and provided with access to personal fabrication in the form of entry-level FDM 3D printing platforms. I2P lab has shown to be a catalyst to create an innovation culture within the host university and amongst innovators in the surrounding region (De Beer and Campbell, 2017). The VUT's I2P lab is fulfilling the main aim of Idea 2 Product lab of providing necessary infrastructure to produce small batches of niche products. This is envisaged to contribute towards jobs creation and to assist poor community's regions to boost their economic level (De Beer and Campbell, 2017).

5. The Growth of Idea 2 Product (I2P) ® Lab in South Africa and Globally

The entry-level FDM 3D printing technology provides a platform for virtually everyone to design quickly and faster based on their innovative and creative thinking, since "*Real Innovation Comes from Within*" (Makerstation, 2017). In the last ten years, the technology has provided a powerful foundation for STEM, innovation and creativity for everybody from all ages. The Idea 2 Product serves as a public-access entry-level FDM 3D printers and Fused Deposition Modelling facilities for innovation, education and creative engagement for students, researchers, entrepreneurs and communities. The Idea 2 Product (I2P) ® Lab enables advanced manufacturing, creates an enabling environment to empower people to turn their creative ideas into reality i.e. creating a 3D model prototypes and to reduce the time to market of the products (CSUVentures, 2013).

At various universities worldwide, additive manufacturing is unlocking significant opportunities; most especially the entry-level FDM 3D printers. Idea 2 Product (I2P) ® lab was originally launched in South Africa in 2011 and currently, the I2P lab concept has been adopted and implemented in more than 25 platforms active internationally (Idea2Product, 2017). In 2013, David Prawel introduced the Colorado State University to 3D printing with RepRap 3D printer in the Department of Mechanical Engineering, and Idea 2 Product was established and modelled after the Idea 2 Product lab founded at VUT, South Africa (Wohlers and Huff, 2017). Nanyang Polytechnic in Singapore uses an I2P lab concept to establish their AM laboratory called "Additive Manufacturing Teaching Factory Concept" and the laboratory is used in training students and personnel from industries on relevant additive manufacturing technologies based on real industrial applications (Wong *et al*, 2014).

Recently in South Africa, more Idea 2 Product labs have been launched in addition to the existing I2P lab at the VUT. In 2015, the Stellenbosch University opens the I2P lab on the campus for academia and community (I2PLab, 2017). In March 2017, Makerstation at Woodstock in Cape Town launched an Idea

2 Product plus (I2P+) Laboratory with the assistance of the North-West University and Vaal University of Technology (funded by the Department of Science and Technology) to restructure and refine the concept of the lab. Also, two Idea 2 Product labs were established in Ikageng, a township in Potchefstroom (North West province) and at Nelson Mandela University (NMU) in Port-Elizabeth (Eastern Cape province). The laboratories are expected to provide exposure to the local communities using entry-level 3D printing technology, meet social needs and stimulate innovative thinking.

As part of the strategy to introduce additive manufacturing technology into the high schools in South Africa using entry-level FDM 3D printing technologies. In April 2017, the Technology Transfer and Innovation (TTI) unit at the VUT launched Idea 2 Product lab at two township high schools within the Gauteng province known as: Thuto-Lore Comprehensive School and Lebohang Secondary School at Sharpville (Rapulane, 2018). Also, in July 2017, the TTI unit started a facilitation in collaboration with group of educators within the Eastern and Southern Gauteng province, and the aim of the collaboration was to facilitate the transition of AM inclusion in the South Africa educational system. The facilitation was done in partnership with the Technology Innovation Agency (TIA), VUT and Gauteng Department of Education. The educators were trained using entry-level FDM 3D printers at the VUT Sebokeng campus I2P lab in July 2017 (I2PLab, 2018). Furthermore, with the aim to improve teaching and learning, and provide the students/learners the platform to be part of the future of AM/3D printing in South Africa, another I2P labs were launched in two township high schools called: Sizanani-Thusanang Comprehensive School and Thuto-Tiro Comprehensive School, in November 2017 at Sebokeng (Rapulane, 2018).

Some of the universities in the United States (such as Colorado State University, Princeton University**,** Penn State University, Cornell University, University of Connecticut, North Carolina State University, Western Carolina University, Iowa State University, Northeastern University, and Arizona State University) and also, in the United Kingdom some universities, (such as University of Nottingham, University of Exeter, University of Sheffield, and Derby University, etc.) have in-house entry-level FDM 3D printing laboratories within their individual Faculty of Engineering to empower students with basic knowledge of AM and design skills. Such laboratories are also helping students and academia to have a direct hands-on-experience of working with the demands of the fledgling 3D printing works from the industry. The set-up of most of the entry-level FDM 3D printing labs launched in the universities mentioned above are modeled after the Idea 2 Product lab concept launched originally at VUT South Africa (Wohlers and Huff, 2017; Wohlers, 2012). However, some universities did not name theirs AM/3D printing Labs – "Idea 2 Product lab", but different names such as Creative Machines lab, Additive Manufacturing centre/lab, 3D printing library, 3D printing studio, 3D printing lab, 3D digital lab. China universities such as Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, and South China University of Technology; have also embraced additive manufacturing education (Dickens *et al,* 2012; Lin *et al,* 2012 and Hague *et al,* 2016).

6. The Case Studies

This paper presents two case studies to show that an entry-level FDM 3D printing technology is being used to promote additive manufacturing education at the university using I2P lab concepts/facilities. The first case study shows that an entry-level FDM 3D printers can serve as platform to train students, provides hands-on-experience and exposure to additive manufacturing education. The second case study indicates that entry-level FDM 3D printers can serve as platform for technology transfer.

6.1 Case Study 1: Entry-Level FDM 3D Printers as a Platform to Train People using Idea 2 Product (I2P) ® Lab

The entry-level FDM 3D printing facilities can serve as a stimulated manufacturing environment for students within the university and communitive to become more creative, innovative and to make progress faster design (Makerstation, 2017). The I2P lab is well-equipped with computers directly connected with approximately 20 entry-level FDM 3D printers and internet facilities. According to De Beer and Campbell (2017) since the inception of the Idea 2 Product Lab, between 2011 and 2016, approximately 7500 students have been trained with entry-level 3D printers with FDM technology and over 20,000 parts have been designed and printed out or manufactured. This is an indication that South

African government is gradually achieving one of the primary aims for developing South Africa additive manufacturing strategy; which is to ensure AM education at different levels from primary/high schools, higher education institutions (HEI) and to diverse industries (du Preez *et al.* 2017).

In this case study, a primary data was collected through the Head of Department of I2P lab at the VUT Sebokeng campus. The data shows that between July 2016 and July 2017; 200 people (i.e. n =200) were trained and introduced to the fundamental AM technologies using the entry-level FDM 3D printers at the I2P lab as shown in figure 5. The gender of the people trained during this period were: 90 males (45%) and 110 females (55%) as shown in figure 5a; the nationality of people trained were 190 South Africa citizens (95%) and 10 foreign nationals (5%) as indicated in figure 5b; the country of the foreign nationals trained were: Botswana (n =4), DRC Congo (n=3), Lesotho (n =1), while 2 foreign nationals were without passport identity numbers, which make it impossible to identify the country of origin as seen in figure 5c. The participant's means of identification during the training period were also recorded as follows: South African citizens with IDs (n = 185;), foreign nationals with passports (n = 8); foreign nationals without means of identification (n = 2) and minors i.e. Grade 10 & 11 Learners with no IDs (n = 5) as shown in figure 5d; and figure 5e shows the participants age range as follows: 5 -15 (n = 3), 16 - 25 (n = 110), 26 – 35 (n = 66), 36 – 45 (n = 35), 46 – 55 (n =4), 56 – 65 (n = 1), 66 – 75 (n = 1). The age range of the participants implies that 16-25 of age have the highest number of participants which is the active years of every young people and this is period when younger people are trying to choose a career path. This is followed by age ranges from 26-35 and 36-45 respectively; with these age ranges, many of the sampled graduates were already working in different companies and some considered training on AM technologies to complement their existing skills.

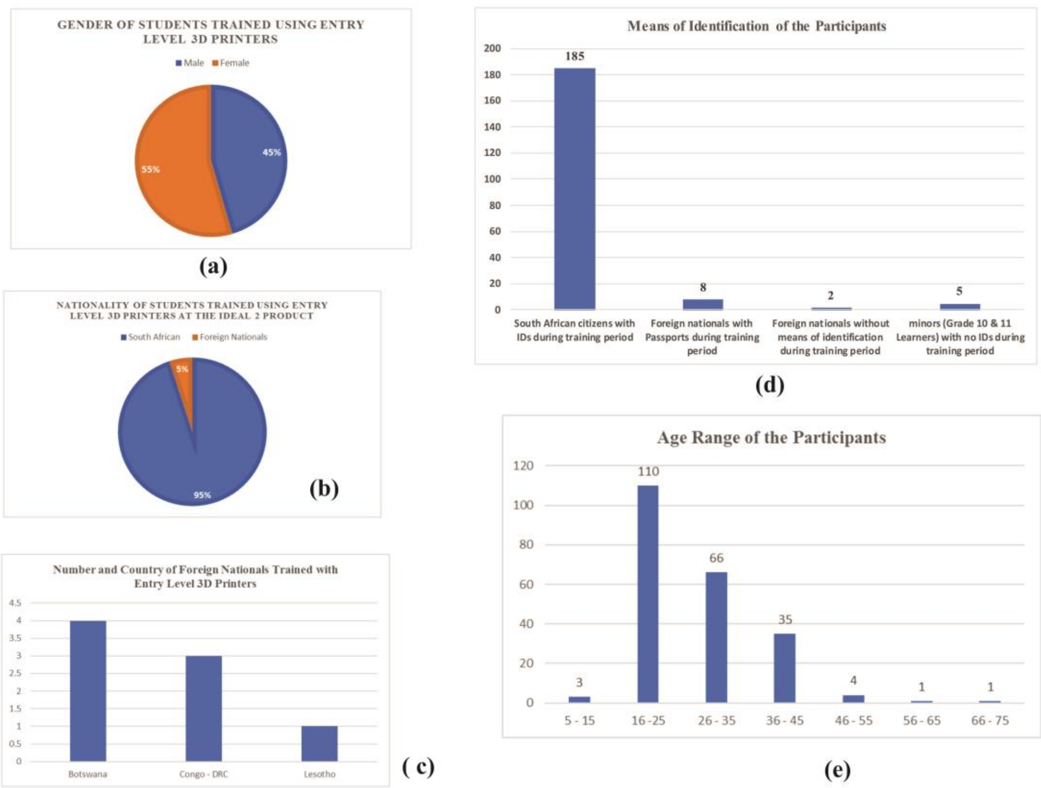


Figure 5: This shows the analysis of primary data collected during the training of 200 people at VUT I2P Lab using entry-level FDM 3D Printers between July 2016 - July 2017. (a) The gender of the participants (b) nationality of participants (c) number and country of the foreign nationals (d) means of identification of participants (e) participant age range participants.

It can be deduced from this case study that entry-level FDM 3D printing machines are suitable for AM education because of their capability to train and equip people such as university students, high school leaners, entrepreneurs, professional, and community members with the fundamental knowledge and advanced hands-on-experience of AM. Lastly, this case study shows that 3D printing lab concepts such as

Idea 2 Product lab can serve as a platform to introduce AM education into the educational system of any college and university worldwide.

6.2 Case Study 2: Entry-Level FDM 3D Printers as a Platform for Technology Transfer through the Idea 2 Product (I2P) ® LAB

Jordaan (2010) defines technology transfer as a process of passing theoretical and practical skills, knowledge, manufacturing processes and technologies from the owner of the technology to a wider range of users. Technology transfer ensures scientific and technological development to become more available in the industry and provides skill development of the university academic staff (Jordaan, 2010). Technology transfer would play a leading role in the development and efficient integration of additive manufacturing education at the university. Technology transfer would also create room for university-industry collaboration, enhance the university academics' and students' relationship with industry and promote more research at different universities.

In a recent paper published by De Beer and Campbell (2017) on the use of Idea 2 Product Labs as a strategy for accelerating technology transfer. The use of entry-level FDM 3D Printers platform provides access to high school learners, university students and individuals that want to create an innovative product from their own ideas. Also, the entry-level FDM 3D printing technologies expose the students to entry-level computer-aided-design (CAD) software. An entry-level FDM 3D printer laboratory concept such as the Idea 2 Product lab can be an alternative to create a platform for AM education; and technology transfer between the university and industry because of its affordability (De Beer and Campbell, 2017).

Campbell and De Beer (2017) stated that the Idea 2 Product (I2P) lab concept supports local innovation and contributes to local economic development projects and create a platform for AM education and research in South Africa. Entry-level FDM AM systems can be a successful tool in the formation of engineers both in the industry and colleges/universities, this allows them to benefit or gain hands-on experience and thereby acquire capabilities from both engineering design skills and new advanced manufacturing technologies (Schelly *et al*, 2015). Moreover, at the VUT AM unit almost 30 students were admitted for one-year internship program. The primary aim of the internship is to expose the interns to AM technologies, gain in-depth knowledge and hands-on-experience of AM processes. The interns came from the neighbouring communities of Sebokeng; the interns were distributed across different sessions of the AM unit such as Idea 2 Product lab, high-end industrial AM machines, design and quality assurance, etc.). The technical staff serve as the AM instructors/educators for the interns and this is a platform for technology transfers.

In addition, Schelly *et al* (2015) study explained that "a democratized use of entry-level AM machines imposes the need for educating people to advanced 3D modelling by using professional CAD software packages or even open freeware packages with enhanced modelling function". This case study supports Schelly *et al* (2015) study as relating technology transfer and the involvement of people (students/interns/academics/professionals/community members) using entry-level FDM 3D printers which could enhance people interest to advance to high-end additive manufacturing machine. For instance, certain number technical staffs at the VUT AM units started their AM journey using entry-level FDM 3D printing technologies at the I2P lab and later advanced to high-end industrial AM machines.

7. Conclusion

Additive manufacturing and 3D printing technologies has been identified as a technology that will play a significant role in the era of Industry 4.0. Entry-level FDM 3D printers have been proven to be a suitable technology for AM education at the high schools, colleges, and universities using the Idea 2 Product lab concept. A typical Idea 2 Product lab at the college or university consists of certain number of entry-level FDM 3D printers for use of the students, academia, interns and professionals within the communities. This paper presents evidence through literature cited and case studies, which indicate that entry-level FDM 3D printing technologies can serve as a platform to train people and provide a platform for AM education. This paper further shows that entry-level FDM 3D printing technologies can serve as platform for technology transfer. Entry-level FDM 3D printers can provide college/university students, interns, professionals, and academics with fundamental AM knowledge which will assist them in developing interest and choose career path in AM technologies. Finally, this paper highlights the importance of the Idea 2 Product Lab concept, its growth and impact both from South Africa and global perspective.

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References

Brett, P.C., Guha, P. M. and Kerry, L. M. (2015). An Assessment of Implementation of Entry-Level 3D Printers from the perspective of small business. *Rapid Prototyping Journal,* 21(5): 528-597.

Buehler, E., Kane, S. K. and Hurst, A. (2014). ABC and 3D: opportunities and obstacles to 3D printing in special education environments. *Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility.* Rochester, New York, USA:ACM.

Caffrey, T., Wohlers, T. and Campbell, R. I. (2016). Exective summary of the Wohlers Report 2016. Fort Collins, Colorado: Wohlers. https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/21223/1/Wohlers Report 2016 Executive Summary.pdf

Campbell, R. I and De Beer, D. J. (2005). Rapid prototyping in South Africa: past, present and Future. *Rapid Prototyping Journal*, 11(4): 260-265.

CampbelL, R.I., De Beer, D.J. and Pei, E., (2011). Additive manufacturing in South Africa: building on the foundations. Rapid Prototyping Journal, 17(2): 156-162.

Campbell, R. I. and De Beer, D. J. (2017). Using-Idea 2-Product Labs as a Strategy for Accelerating Technology Transfer. International Journal of Technology Transfer and Commercialisation, 14(2): 249-261.

CSUVentures. (2013). Colorado State University - Idea-2-Product Lab Presents 3D Printing Workshop at CSU. http://csuventures.org/idea-2-product-lab-presents-3d-printing-workshop-at-csu/. Date of access: 21 Dec. 2017.

CustomPartnet. (2009). Additive Fabrication. http://www.custompartnet.com/wu/additive-fabrication. Date of access: 26 Oct. 2016.

Dar, T. (2016). 11 Universities That Are Leading the World In 3D Printing. http://wonderfulengineering.com/11-universities-that-are-leading-the-world-in-3d-printing/. Date of access: 30 January 2018.

De Beer, D J. (2011). Establishment of rapid prototyping/additive manufacturing in South Africa. The Journal of The Southern African Institute of Mining and Metallurgy, Vol. 111:211-215. www.scielo.org.za/pdf/jsaimm/v111n3/16.pdf

De Beer, D. J., and Du Preez, W.B. (2015). Implementing the South Africa additive manufacturing technology roadmap – The role of an Additive Manufacturing Centre of Competence. *South African Journal of Industrial Engineering.*26(2):85-92.

De Beer, D, J. (2016). South African Additive Manufacturing Landscape/Growth of 3D Printers, 1991-2015.

Dickens, P., Reeves, P. and Hague, R. (2016). Additive Manufacturing Education in the UK. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-01-Dickens.pdf.

Du Preez, W., De Beer, D., Greyling, H., Prinsloo, F., Sciammarella, F., Trollip, N., Vermeulen, M. and Wohlers, T. (2016). A South African Additive Manufacturing Strategy. Department of Science and Technology.

Hague, R., Reeve, P. and Jones, S. (2016). Additive manufacturing: mapping UK research into 3D printing. https://www.gov.uk/government/publications/additive-manufacturing-mapping-uk-research-into-3d-printing. Date of access: 01 Dec. 2017.

Havenga, S. (2017). Entry Level 3D Printing – Idea 2 Product Lab. Information Supplied by Sarel Havenga, Technology Transfer and Innovation, I2P Lab VUT Science and Technology Park, Sebokeng Campus.

Huang, S. H., Liu, P., Mokasdar, A. and Hou, L. (2013). Additive manufacturing and its societal impact: a literature review. *International Journal of Advanced Manufacturing Technology,* 67(5-8): 1191-1203.

HS3DP (Home Shop 3D Printing). 2016. 3D Printing Process and Technologies. http://homeshop3dprinting.com/3d-printing-qa/3d-printing-process-and-technologies/. Date of access: 21 Dec. 2017.

I2PLab. (2017). Idea2Product Lab Stellenbosch. 3D printing facility - low cost, easy access. blogs.sun.ac.za/idea2product/about_prices/. Date of access: 13 Dec. 2017.

I2PLab (2018). Idea 2 Product Lab facebook Page. https://web.facebook.com/Idea2ProductLab/?ref=br_rs. Date of access: 16 January 2018.

Idea2Product. (2017). Speeding Innovation, Creativity and Product Development. https://idea2product.net/deon_de_beer/. Date of access: 21 Dec. 2017.

Jordaan, G. D. 2010. A Business Model for Rapid Prototyping in South Africa. *Academic Journal.* Annals of DAAAM & Proceedings; 2010, p1561. http://www.freepatentsonline.com/article/Annals-DAAAM-Proceedings/246014346.html.

Kostakis, V., Niaros, V. and Giotitsas, C. (2015). Open Source 3D printing as a means of Learning: An educational experiment in two high schools in Greece. *Telematics and Informatics,* 32(1): 118-128.

Lacey, G. (2010). 3D Printing Brings Designs to Life. *Technology Education Journal/Directions.* 70(2): 17-19.

La Grange, J., Becker, L. and De Beer, D. J (2014). Entry Level FDM 3D Printer Produced Parts Satisfying Niche Market in Industry. *Proceedings of the 2014, RAPDASA Conference,* Rapid Product Development Association of South Africa, Stellenbosch, South Africa.

Lin, F., Zhang, L., Zhang, R. and Zhang, T. (2012). Innovative education in additive manufacturing in China. https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-02-Lin.pdf.

Lotz, M.S., de Beer, D. J. and Pienaar, H.C.V.Z. (2013). Entry-level additive manufacturing: Comparing geometric complexity to high-level machines. AFRICON, 2013. [Abstract].

Makerstation. (2017). Idea to Product plus Lab. http://makerstation.co.za/i2plab/. Date of access: 17 January 2018.

McNally, K. (2011). 3D Printing Brings Designs to Life. https://euclidgroup.wordpress.com/2011/04/10/3d-printing-brings-designs-to-life/. Date of access: 19 January 2018.

Minetola, P., Luliano, L., Bassoli, E. and Gatto, A. (2015). Impact of Additive Manufacturing on Engineering Education – Evidence from Italy. *Rapid Prototyping Journal, Emerald Group Publishing Ltd,* 2(5):535-555.

Nettleton, K. T. and Lennex, L. (2013). Cases on 3D Technology Application and Integration in Education. *Advances in Early Childhood and K-12 Education.* IGI Global Publisher.

Palermo, E. (2013). What is Laminated Object Manufacturing?. https://www.livescience.com/40310-laminated-object-manufacturing.html. Date of access: 02 July 2018.

Pei, E., Campbell, R.I. and De Beer, D. J. (2011). Entry-level RP Machines: How well can they cope with geometric complexity? *Assembly Automation,* 31(2): 153-160.

Pei, E. (2015). Entry-Level Additive Manufacturing: The Next Frontier. Rapid Prototyping Journal, 21(5).

Pennstate. (2017). Penn State to offer new additive manufacturing and design graduate degrees. http://www.ime.psu.edu/news/amd-degrees-sp17.aspx. Date of access: 18 January 2018.

Rapulane, S. (2018). Idea to Product Labs spring up in township schools. http://www.vut.ac.za/idea-to-product-labs-spring-up-in-township-schools/. Date of access: 16 January 2018.

Schelly, C., Anzalone, G., Wiljnen, B and Pearce, J. M. (2015). Open-Source 3D Printing Technologies for Education: Bringing Additive Manufacturing to the Classroom. *Journal of Visual Languages and Computing*, 28: 226-237.

Wittbrodt, B. T., Glover, A. G., Laureto, J., Anzalone, G. C., Oppliger, D., Irwin, J. L. and Pearce, J. M. (2013). Life-cycle economic analysis of distributed manufacturing with open-source 3D printers. *Mechatronics,* 23(6):713-726.

Wohlers, T. (2012). Idea 2 Product Labs. https://wohlersassociates.com/blog/2012/09/idea-2-product-labs/. Date of access: 21 Dec. 2017.

Wohlers, T. and Huff, R. (2017). CSU's Idea2Product Lab. https://wohlersassociates.com/blog/2017/10/csus-idea2product-lab/. Date of access: 21 Dec. 2017.

Wong, D. S. K., Zaw, H. M. and Tao, Z. J. (2014). Additive manufacturing teaching factory: driving applied learning to industry solutions. *Virtual and physical Prototyping,* 9(4): 205-212.

Zein, I., Hutmacher, D, W., Tan, K. C. and Teoh, S. H. (2002). Fused deposition modeling of novel scaffold architectures for tissue engineering applications. *Biomaterials.* 23(4):1169-1185.

Appendix H

Framework for Effective Additive Manufacturing Education: A Case Study of South African Universities.

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Abstract

In this era of First Industrial Revolution, FIR, also referred to as 'Industry 4.0', AM has been recognised as one of the nine technologies of industry 4.0, such as Internet of Things, Big Data and Analytics, Cybersecurity, etc., that will revolutionize different sectors and bring about a significant transformation in industrial production and manufacturing industries. The South Africa (SA) government through the Department of Science and Technology has invested significantly towards research in additive manufacturing technology growth and as AM technology is growing in SA, there is a need for more educated personnel and industry professionals in the field. In 2013, during a stakeholder workshops in SA, education was highlighted as one of the main priorities to ensure a successful adoption of additive manufacturing technology in SA. AM technologies is still at an infant stage and to reap the full potential of this technology, its inclusion in the educational curriculum is very crucial. To achieve this, an effective AM framework must be developed and currently, there is no specific framework for AM education at the universities. Therefore, this study focuses on "Additive Manufacturing Education" and aimed to investigate the impacts of AM technology and thereby, proposed a framework for effective AM education using selected SAs' universities as the case study. This study used a structured questionnaire and followed by open-ended questions distributed among university students and academics to collect main data for the study. The contribution of this study towards the existing body of knowledge in AM technology, specifically 'AM education research' was in the form of proposed framework for AM education at the university. The proposed framework allows the government sectors/department/bodies and giant players in AM in SA to see the need to invest significant towards the advancement of AM technology, education and research activities at the university.

Keywords: Additive Manufacturing Education, Additive Manufacturing, 3D printing, South African Universities.

1. INTRODUCTION

Additive manufacturing (AM) which is also known as 3D printing technology. According to Wohlers (2010) AM is the official industry standard term (ASTM F2792) for all applications of the technology. It is defined "as the process of joining materials to make objects from 3D model data, and it is usually layer upon layer, as opposed to subtractive manufacturing methodologies". Additive manufacturing has been identified as a 21st century emerging technology and is becoming popular within the academia and several industries globally. Some of the characteristics of AM is that it reduces waste material, brings down labour costs, speeds up the development and test phase, and allows for product customisation and the ability to make complex metal parts (CSIRO, 2015). AM helps to reduce mistakes and delays to a minimum and produce winning products (Wohlers, 2011).

South Africa is one of the active countries on the Africa continent promoting additive manufacturing technology, education and research both in the academia and industry. It is predicted that AM technology will play a significant and game-changing role in the Fourth Industrial Revolution, FIR, also known as 'Industry 4.0'. AM technology has been active in South Africa for past 26 years and it promises to play an ever-growing role in efforts to re-industrialise the economy of South Africa (NSTF, 2016). During the National Science and Technology forum (NSTF) in March 2016, a discussion forum for Science. Engineering. Technology for Socio-Economic Growth in South Africa; the panel discussions focused on AM in South Africa and it was stated that AM sector of South Africa is led by higher learning institutions and science councils; and the leading institutions are Central University of Technology (CUT) and Vaal University of Technology (VUT) where products are being made on a regular basis for various sectors. CUT focuses primarily on serving the medical industry while VUT services the tooling and casting industries". North West University and Stellenbosch University are also part of the AM players in South Africa (NSTF, 2016). It was noted that industry-led research is essential for AM to succeed in South Africa (NSTF, 2016).

Appendix G

Declaration

This is to declare that I, Annette L Combrink, accredited language editor and translator of the South African Translators' Institute, have language-edited the thesis by

M.O. Alabi

with the title

Framework for effective Additive Manufacturing education at South African universities

Prof Annette L Combrink

Accredited translator and language editor

South African Translators' Institute

Membership No. 1000356

Date: 13 November 2018

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Appendix H

The list of participants that responded to the pilot survey of the questionnaire

S/N	Name of Respondents	Position	Name of University or Organization	Completed and feedback
1	Prof Dr Harm-Jan Steenhuis	Professor	Hawaii Pacific University, USA	Did not complete the questionnaire but provide a feedback on how to improve the questionnaire.
	Prof David Walwyn	Professor	University of Pretoria, School of Technology Management	Completed the questionnaire and with feedback
3	Professor Esther Akinlabi	Professor	University of Johannesburg, Vice Dean: Teaching and Learning, Faculty of Engineering and the Built Environment,	Did not complete the questionnaire, received the questionnaire and requested that her colleague (Dr Erinosho, Mutiu) to complete the questionnaire and provide feedback.
4	Dr Erinosho, Mutiu	AM Researcher	University of Johannesburg	Completed the questionnaire and with feedback
5	Dr Jan Janse Van Rensburg	Senior Lecturer	North West University, School of Mechanical and Nuclear Engineering	Completed the questionnaire and with feedback
6	Mr Thys Taljaard	Senior Technician	NWU – Laboratory for Instrument Maker	Completed the questionnaire and with feedback
7	Mr Dave Bullock	AM Expert	Rapid 3D JV (PTY) LTD	Completed the questionnaire and with feedback
8	Mr Ogunlana Musibau	Doctoral Student	University of Johannesburg	Completed the questionnaire and with feedback
9	Mr David Lucak	Master Student	University of the Witwatersrand	Completed the questionnaire and with feedback
10	Mr David A. Mauchline	AM Expert	Vaal University of Technology, Technology Transfer & Innovation	Completed the questionnaire and with feedback.
11	Mr Lukas Steenkamp	AM Researcher	R & D Stellenbosch University Learning Factory	Completed the questionnaire and with feedback.