

# 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 (AM) research and activities within selected universities in the Republic of South Africa (SA).

**Design/methodology/approach** – The paper is a general review of AM education, research and development effort within selected South African universities. The paper begins by looking at several support programmes and investments in AM technologies by the South African Department of Science and Technology (DST). The paper presents South Africa's AM journey to date and recent global development in AM education. Next, the paper reviews the recent research activities on AM at four selected South African universities, South Africa AM roadmap 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 an education perspective.

**Findings** – The main lessons that have been learnt from South African AM research activities within selected universities are as follows: AM research activities at South African universities serve as a platform to promote AM education, and several support programmes and investments from South Africa's DST have greatly enhanced the growth of AM across different sectors, such as medical, manufacturing, industrial design, tooling, jewellery and education. The government support has also assisted in the actualisation of the "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 South Africa's universities have shown that it is not too late for developing countries to start and embrace AM technologies both in academia and industry. Based on a SWOT analysis, the future prospects of AM technology in SA are bright.

**Practical implications** – Researchers/readers from different backgrounds such as academic, industrial and governmental will be able to learn important lessons from SA's AM journey and the success of SA's AM researchers/practitioners. This paper will allow the major investors in AM technologies and business to see great opportunities to invest in AM education and research at all educational levels (i.e. high schools, colleges and universities) in South Africa.

**Originality/value** – The authors believe that the progress of AM education and research activities within SA's universities show good practice and achievement over the years in both the applications of AM and the South African AM strategy introduced to promote AM research and the educational aspect of the technologies.

**Keywords** Additive manufacturing, 3D printing, Additive manufacturing education, South African universities

**Paper type** General review

## 1. Introduction

Additive Manufacturing (AM), also referred to as 3D printing (3DP), is a process of creating a physical object from a three-dimensional digital model layer upon layer. AM has been identified as a twenty-first century emerging technology and is becoming popular around the world within academia and manufacturing industries. AM has a wide variety of potential application areas such as medical and dental, automotive, aerospace, general manufacturing. AM education can be

introduced into the university's systems through cutting-edge research in collaboration with university academics and industry partners. AM (previously also referred to as rapid prototyping) in South Africa (SA) started in 1991 with a single 3D Systems SLA 250. R&D has been identified as a promising field where AM is influencing the education sector.

SA is one of the active countries on the African continent promoting AM research, both in academia and industry through various support programmes, for instance, South African Department of Science and Technology (DST) has invested significantly towards research in AM over the years. More so, the primary aim of the South African AM strategy is to promote AM education and its awareness (Du Preez *et al.*,

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2016). South African 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 named "Aeroswift", was officially launched in 2011 in collaboration with Aerosud (an aviation manufacturing solutions provider) and the SA Council for Scientific and Industrial Research (CSIR), and funded by the South African DST (Scott, 2017b; Oberholzer, 2018). In 2017, a report from the Industrial Development Corporation (IDC) of SA mentioned that an investment of R17m (equivalent to approximately US\$1.2m) on a metal 3DP, that is, a start-up facility that manufactured metal 3D printed parts called "Metal Heart" was initiated and these investments are part of the South African Government strategy to create a competitive advantage in AM and provide jobs in priority industries, such as 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 Fourth Industrial Revolution (MicroFabricator, 2017).

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 USA 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 revolutionise colleges, universities and schools, and it has brought 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 in the education sector, a non-competitive collaboration between AM companies (i.e. the AM systems and material manufacturers) 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 South African National Science and Technology Forum (NSTF, held in March 2016), it was identified that the SA AM sector is led by higher education institutions (HEIs) (i.e. the universities) and science councils. The leading institutions in AM/3DP 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 focusses primarily on serving the medical industry, whereas 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 and the in-house industrial grade AM platforms (as well as entry-level 3D printers) available at these universities.

This 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 SA universities; Section 6 presents sustainability of AM from an education perspective, followed by conclusions; Section 7

evaluates the present and future prospects of AM education and research activities at SA using SWOT analysis; and Section 8 presents the conclusion.

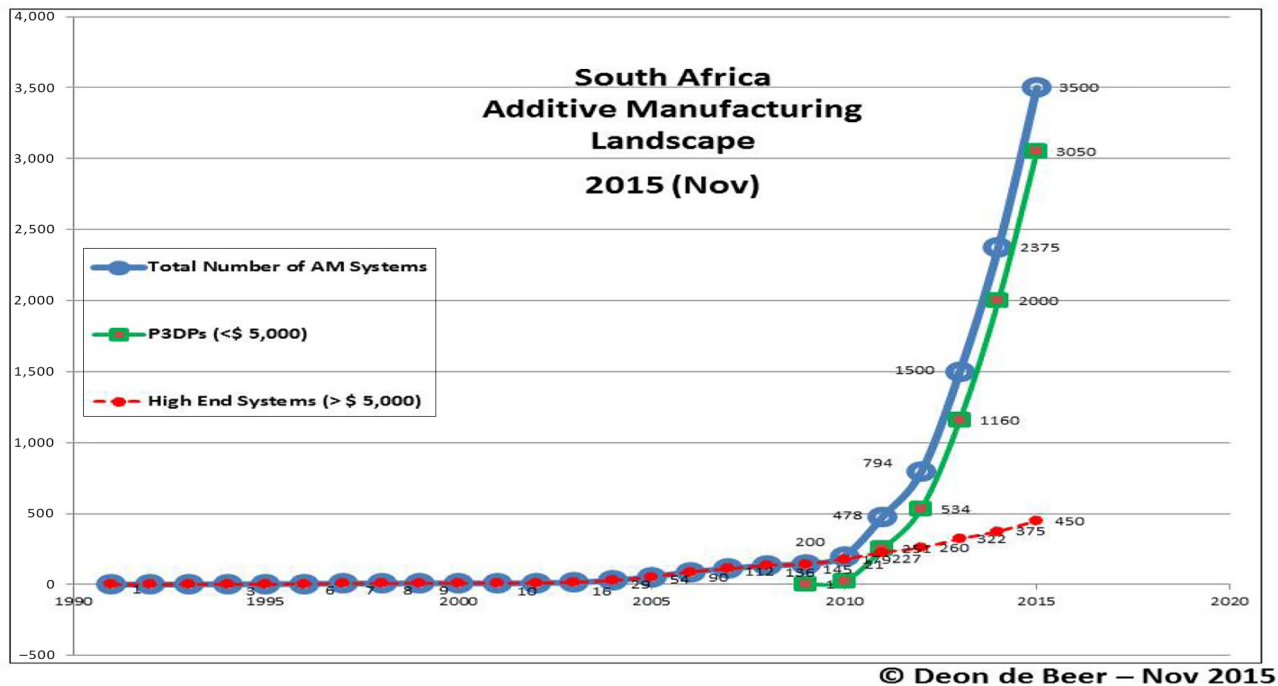
## 2. South Africa's additive manufacturing journey

SA has been active in AM for the past 26 years. Although SA had late start with rapid prototyping (now known as AM), approximately ten years after the technology had been accepted by the international community (De Beer, 2011). It was recorded that from 1991 to 1994, only three AM systems were available in South Africa (De Beer, 2011). The first 3DP system, a 3D Systems SLA 250 was introduced in 1991. In 1994, the CSIR purchased two FDM 1500 machines which were later upgraded to FDM 1650 s. 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, 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 which brought the number of AM machines in SA to seven. By 1998, of the seven AM systems in South Africa, six were owned by academic or research organizations (De Beer, 2011). In 2000, the Rapid Product Development Association of South Africa (RAPDASA) was officially launched, as the representative body of the AM and product development community in South Africa (Du Preez and De Beer, 2006). RAPDASA has therefore played a significant role in raising AM/3DP technology awareness through their annual conference and international links such as the Global Alliance of Rapid Prototyping Associations (Kunniger, 2015).

The steady growth of AM system implementation took the overall number of AM machines to 17 by 2003. Of these, only two were owned by private organizations while the other 15 were located within universities and science/research councils (Campbell and De Beer, 2005; Wohlers, 2004). In 2004, the trend towards AM/3DP technology in SA continued to grow exponentially, and the market for AM systems, especially the desktop 3DP machines in SA continued to increase. Between 1994 and 2004, it was estimated that 32 AM machines were available in SA (Campbell and De Beer, 2005). Between 2004 and 2008, there were approximately 138 AM machines available across SA (Campbell et al., 2011). By 2013, approximately 1500 AM machines were available, and in 2015, it was estimated that 3500 AM machines were in use (De Beer, 2015b), as shown in Figure 1. Of the 3500 AM machines recorded between 1994 and 2015, 85 per cent of them were entry-level desktop 3D printers and 15 per cent represented the high-end industrial grade technologies.

A reasonable number of these AM systems are in science councils and HEIs in SA. It is evident that the AM landscape and 3DP sales in SA has experienced a significant growth within the past 26 years, which implies that the future of AM in the country is bright compared to other African nations. More so, the number of high-end industrial grade AM machines at CUT and VUT has 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. The NLC and Aerosud aims to develop AM techniques and the world's largest 3D printer (Wild, 2014).

**Figure 1** South African's AM Landscape/Growth of 3D Printers, 1991-2015 (Supplied by: Deon de Beer)

The project is called “Aeroswift”, funded by South African DST (Science Forum, 2015). The Aeroswift AM Machine has a large build volume of up to 2 m x 0.6 m x 0.6 m, which results in the production of large 3D printed parts. In 2017, the Aeroswift AM system produced the first three demonstrator parts which included 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 teams have discussed with Boeing and Airbus, the use of 3D printed titanium parts in the aircraft, which will reduce the weight significantly and lower the production cost, for when the commercial production is expected to begin in 2019.

According to Koslow (2016), SA’s public sector has invested around ZAR 358 m (about US\$24.5m) in AM technology R&D, and it is likely to increase in the near future. In addition, the DST committed ZAR 30.7 m (€2m) towards a collaborative R&D 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 AM 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 3DP of 99.99 per cent 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,

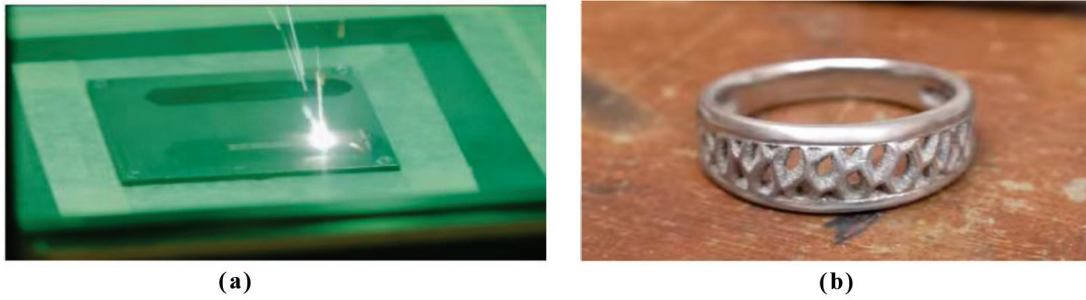
medicine, electronics and also for high-performance aerospace parts. Platinum has greater benefits and it is extremely corrosion resistant (Scott, 2017b). The “Platforum” team currently explores the possibility of using the benefits of platinum as leverage to investigate whether platinum could be additively 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 allowed SA to showcase the potential of 3DP of Platinum Group Metals, 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.

### 3. South African additive manufacturing RoadMap

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 domains, there is a need to develop a comprehensive and easy-to-implement AM technology road-map. During the 2012 RAPDASA conference and AGM, it was recommended to develop a SA National Additive Manufacturing Road-map. In 2013, the DST approved the development of the SA AM Roadmap (Du Preez and De Beer, 2015). The purpose of the 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 technologies” (Du Preez and De Beer, 2015a).



Figure 2 South Africa's first pure platinum 3 D printed ring



**Notes:** (a) Shows the processes of 3DP the ring using EOSINT M 280 machine from EOS; (b) shows the 3D printed ring using 99.99% of platinum powder material  
**Source:** (Scott, 2017a)

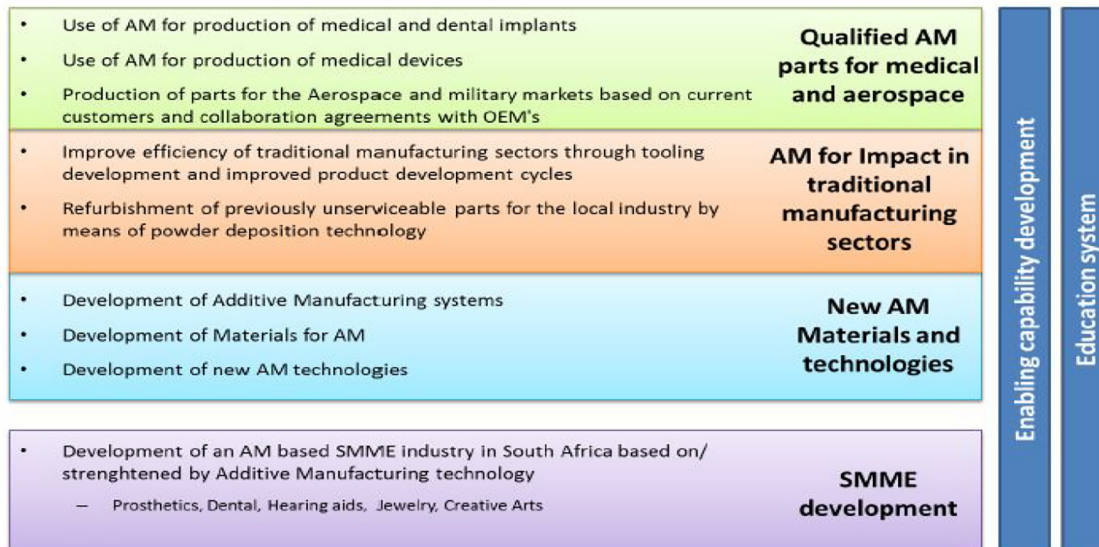
Furthermore, the SA AM technology roadmap recommendation was presented to the DST and RAPDASA in 2015 during the annual conference (Du Preez and De Beer, 2015a). The road-map comprised four focus areas (Qualified AM parts for medical and aerospace, AM for impact in traditional manufacturing sectors, New AM materials and technologies and SMME development) as presented in Figure 3. The roadmap attempted to create an enabling capability development environment and promote AM education at the colleges and universities.

Alongside the SA AM Road-map (Du Preez and De Beer, 2015a), commercialisation of AM platforms for SA industries, as shown in Figure 4, was also suggested. The concept of a national Additive Manufacturing Centre of Competence (AMCoC) framework was suggested to primarily serve as the implementation vehicle for the SA AM Roadmap. Almost all

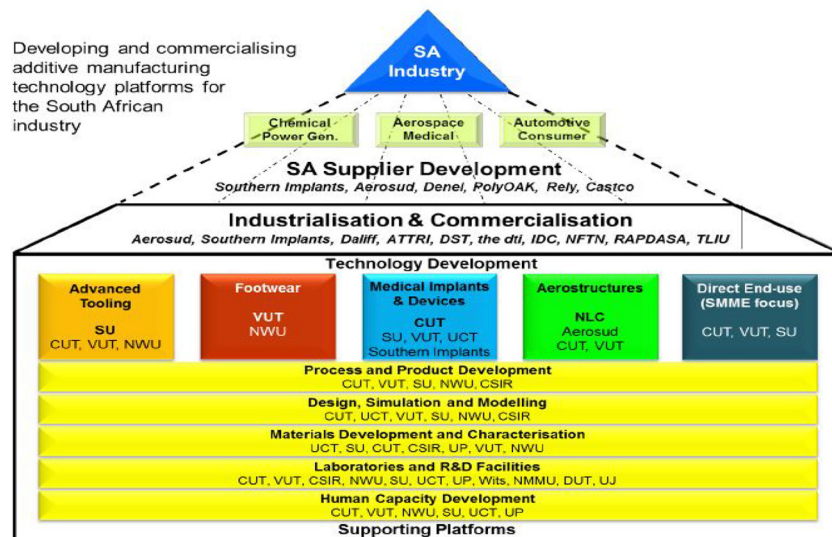
the SA universities were included as collaborators for the SA AMCoC, as shown in Figure 4 (Du Preez and De Beer, 2015a). The SA industries that were targeted in the AMCoC are chemical and power generation, aerospace and medical and automotive and consumer, and the SA supplier development part comprises Southern Implants, Aerosud, Denel, PolyOAK, Rely and Castco. The industrial and commercialisation groups 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 of AM applications (i.e. advanced tooling, footwear, medical implant and 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

Figure 3 Recommendations of the South African AM Technology Road-map



Source: (De Beer and Du Preez, 2015a)

**Figure 4** The collaborators of the South African AM centre of competence

Source: (Du Preez and De Beer, 2015)

characterisation, laboratories and R&D facilities and human capacity development. As part of the long-term plan for the SA AM strategy, selected universities and research institutes were included in the National Centre of Competence: CUT, VUT, SU, NWU, CSIR, University of Cape Town, University of Pretoria, Wits University, Nelson Mandela University, Durban University of Technology and University of Johannesburg.

#### 4. Recent global development in additive manufacturing education

AM education can be described as a platform or vehicle through which AM technologies 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 to the universities. In addition, AM educational and training programmes should also be directed to artisans, technicians, technologists, engineers and scientists already working in diverse industrial sectors. Active AM research or technology transfer activities at 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 the technologies and allow them to choose a career path in AM. Globally, many industrial sectors are rapidly adopting AM whereas some industries are using the technology to complement their existing traditional manufacturing systems.

Therefore, in SA, there is a need for graduates with basic knowledge and hands-on-experience that would provide them the opportunity to take up positions in various AM industries internationally. SA is not an exception in this development; industries and companies within SA are embracing this technology gradually. To effectively promote AM education and training at the colleges and universities, an AM course or curriculum needs to be developed which is suitable for the SA educational context. At

the VUT, a 3D Printing Laboratory technology laboratory called (Idea 2 Product [I2P] Lab<sup>TM</sup>) was established in 2011; by 2017 approximately six I2P Labs, which had been launched in six high schools, are expected to be extended to some other high schools in 2018. Based on this initiative from VUT, it has shown significantly that the introduction of AM technology is encouraging younger generations to develop interest with the aim to pursue science and engineering education at the university and eventually promote a career path in AM.

According to Platt (2015), based on a study conducted by a data analytics company, the findings have shown that 35 per cent of recent engineering job opportunities in certain fields require basic knowledge/skills of AM technology, with such fields including: biomedical engineering, electrical engineering, industrial engineering, software engineering and transportation industries. More so, the findings show that most of these companies are having difficulties in finding suitable engineering candidates with AM skills to take-up related positions (Platt, 2015; Huston *et al.*, 2015). Despite the tremendous growth in the field of AM technology in recent years, there are few studies that centre on AM education *per se*.

According to Williams and Seepersad (2012), AM education is of crucial importance at the moment; however, the lack of knowledge or experience of AM technologies is one of the barriers to achieve widespread adoption. Williams and Seepersad (2012) addresses the "Design for Additive Manufacturing" and curriculum for undergraduate/postgraduate AM courses at the University of Texas, and this study was illustrated using both problem-based and project-based approaches, which enables students with the opportunities to acquire hands-on experience with AM technologies. The AM curriculum was developed and the general class structures for AM curriculum focusses on the following topics, namely, identifying AM opportunities, AM project planning and economics, AM concept generation, AM embodiment design and AM detailed design. The outcomes of

the introduction of an AM curriculum to both undergraduate and postgraduate courses 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, i.e. from idea conception to AM part fabrication to final testing (Williams and Seepersad, 2012).

Dickens *et al.*, (2016) discusses the journey of AM education in the UK. The paper is a comprehensive review of various AM research activities in the UK. AM education started in the UK in March 1992 with a seminar organized by the Institution of Mechanical Engineers coupled with an industrial exhibition. More so, the UK has an effective AM research landscape that includes educational activities and organization involvement (Dickens *et al.*, 2016). Furthermore, Despeisse and Minshall (2017) conducted a study entitled “Skills and Education for AM: A Review of Emerging Issues” addressing 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. The Despeisse and Minshall (2017) study reviewed the current educational and training programmes in AM for both undergraduate and postgraduate courses ranging from full academic programmes to short courses for professionals in the industry. The study made some recommendations for an education programme to enhance the AM skills for students, lecturers, designers, engineers and managers in industry (Despeisse and Minshall, 2017).

Waseem *et al.* (2016) also conducted a national 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 the study was “to examine and shed light over the current education system of Pakistan without opting for modern 3DP technology in the classroom learning and how it can be beneficial for educationist”. The study analysed the Pakistan traditional education system when compared to the international present-day education system with AM/3DP technology and the way this technology has revolutionized today's educational system (Waseem *et al.*, 2016). Radharamanan (2017) conducted a study on AM in manufacturing education, through the development and implementation 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 course with hands-on-experience. Based on the findings from the study, it shows that the AM elective courses introduced, provided the students with the privilege to learn about the fundamental AM processes and were trained using different design tools such as 123D Design, ProE and Netfabb.

Drakoulaki's (2017) study entitled “3D Printing as Learning Activity in the Higher Education”, includes a case study of a robotics prototyping course at the University of Oslo, Norway. The study focusses 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”. The study also explores the research question on how 3DP technology does serve as a tool for

learning and also how do the lecturers and students perceive the significance of 3DP for learning purpose at the university.

Furthermore, Minetola *et al.* (2015) conducted research entitled “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 a Master of Science programme in Mechanical Engineering at “The Polytechnic University of Turin in Italy” as the case study; The Polytechnic University of Turin is a top Italian university, which is a partly public engineering university. The research methodology for the study was “questionnaire survey”, which consisted of both closed- and open-ended questions. The questionnaire was designed specifically to evaluate the relevance of entry-level AM machines within the learning environment and as a tool for project development. The outcome of the research shows a positive impact on mechanical engineering students 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 educational institutions and industry. For example, in 2017, General Electric (GE) committed US\$10m over the following five years to school and college programmes in the USA to develop future talent in 3DP/production technologies through AM education. GE believes that “enabling educational institutions to provide access to 3D printers will help accelerate the adoption of AM worldwide”, and this collaboration is intended to further strengthen GE's position in rapidly growing markets of AM (Optics, 2017). Similarly, as part of industry's collaboration on an AM education programme, in 2017, two USA-based companies announced a training collaboration to focus on AM education. The purpose of the collaborative training is to promote the proper utilisation 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 AM (PRNewswire, 2017).

In SA, established training programmes tailored towards the needs of AM education and industry is limited, because the technology is still very new. 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” and during a stakeholder workshop in 2016, some essential measures to ensure AM education at different levels (i.e. primary/secondary Schools to higher education institutions and diverse industries) were identified as listed below:

- to develop a short-, medium- and long-term educational framework for AM;
- to ensure school-level interventions to facilitate exposure to AM technology;
- to provide widespread access to 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 within colleges and universities;
- to establish a dedicated bursary programme for both pre- and post-graduate studies in the field of AM and 3DP; and
- to secure National Research Foundation (NRF) and DST Research Chairs for AM and to establish national AM centres at strategic locations.



As part of the recent development in AM education, some universities across the globe have introduced courses, for example, in the USA, CO State University has introduced “MECH 502 - Advanced/Additive Manufacturing Engineering” as part of the course undertaken towards a Masters in Mechanical Engineering (CSU, 2016); University of Maryland started a master’s programme in AM for Fall 2017 which was designed purposely for working engineers and technical staff with core courses such as engineering design methods, 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 Fall 2017 (Pennstate, 2017). Some universities in the UK, including University of Sheffield started a master’s program by research [MSc (Res)] in Additive Manufacturing and Advanced Manufacturing Technologies within the Department of Mechanical Engineering (UoS, 2016); Derby University launched a Master of Science in 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). Some universities in China have incorporated AM education, including Tsinghua University, Xi’an Jiaotong University, Huazhong University of Science and Technology and South China University of Technology (Dickens *et al.*, 2012; Lin *et al.*, 2012; Hague *et al.*, 2016).

As AM education is rapidly growing worldwide, Briggs (2014) identifies certain benefits in the educational sector as highlighted below:

- increase in student exposure and enhanced creativity;
- provision of adequate educational technology and balanced curriculum;
- encouragement of sharing and collaboration and increase in greater level of customisation;
- making of manufacturing and designing a common knowledge; and
- success in preparing students for design and careers in AM technology.

In 2016, the National Forum on AM Education and Training was held at the Penn State University, which brought so many educators and industries together to address the need for AM technologies to be adapted into engineering education. 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 the need for STEM educators, university academics, researchers and industry to collectively adapt and develop educational strategies to prepare students for twenty-first century STEM manufacturing techniques such as AM (ITEEA, 2016).

## 5. Recent applications of additive manufacturing research activities at selected South African universities

In a study conducted by Campbell *et al.* (2011), it was shown that major universities in SA have a strong presence in manufacturing-related research, and the study also established that approximately 48 per cent of all SA universities have AM/3DP facilities in-house. Because of this, AM education within

science and engineering is rapidly growing among undergraduate and postgraduate students; also, the academic staff is using the facilities for research purposes. The key reason for AM technology at SA universities is to promote AM education. On the other hand, some selected South African universities have both the “high-end industrial AM machines” and “entry-level desktop 3D printers” for academic, research and commercial purposes. For the purpose of this paper, the South African universities selected are CUT, VUT, NWU and SU. These universities were selected because of the availability of AM in-house facilities at their campuses and the presence of an active AM research group; the facilities at these selected universities comprise both high-end industrial grade and entry-level AM machines. This section of this paper presents the recent applications and AM research activities at the selected SA universities as further detailed in the following sub-sections.

### 5.1 Central University of Technology

CUT is a University of Technology in Bloemfontein, a city in central South Africa. In the past two decades, the university has been involved in extensive research in AM, and CUT is regarded as a leading AM centre. In 1997, the Centre for Rapid Prototyping and Manufacturing (CRPM) was established. At that time, AM technology was in its infancy worldwide. CRPM serves as both a commercial and research centre, bridging the gap between the faculty, academic staff and industry (Jordaan, 2010). The CRPM has proven that enabling “Rapid Manufacturing” platform creates room for higher education institutions to operate as entrepreneurial universities in SA (Jordaan, 2010). CRPM undertakes 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 has more than ten high-end industrial grade AM machines which makes it one of the best-equipped AM centres with world-class facilities within the Southern Hemisphere. At the CRPM, the AM research focusses on three distinct areas, namely, medical applications, prototyping and rapid tooling with funding support from the DST, Technology Innovation Agency (TIA) and the NRF. Based on a variety of AM research on medical applications, the centre became the first in SA to receive ISO 13485 certification for 3DP of medical devices and the first AM centre with ISO 13485 certification in Africa.

CUT was awarded a Research Chair in Medical Product Development with a grant through the DST in 2012, which boosted the university research activities for medical purposes using AM technology (Helsel, 2015); thus 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 SA higher educational system is that a unique course in mechanical engineering was developed to suit AM technology within the SA context, and it created an opportunity to develop multi-disciplinary research that evolved the manufacturing systems and enhanced 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 where medical procedures were conducted involving the use of 3DP technology on 12 patients, including 2 patients that had 3 D-printed titanium jaw implants inserted (Helsel, 2015). Other research activity included a teenage boy born without ear canals, who at the age two had 60 per cent hearing ability and difficulties trying to communicate. He received two ears at the Groote Schuur Hospital with the assistance of CRPM and the Carl and Emily Fuchs Foundation, which was achieved using 3DP technology. The two ears were designed and manufactured with a positioning device which assisted placement of the prosthetic implants and the external prostheses. 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 prosthesis, as shown in Figure 5(a). A 3D printed positioning device was used for the implants, and within three months of the healing period, the implants were shown to place the prosthetic ears, and impressions were used to cast silicone prosthetic ears that matched the patient's skin tone/colour (CRPM, 2017b).

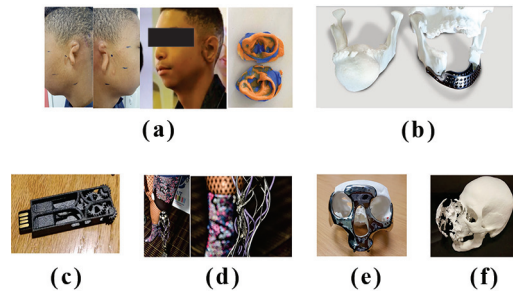
In more recent years, Materialise (an active company in the field of AM) donated funding to CRPM to assist some patients with life-changing interventions and to introduce students to the different benefits of 3DP technology in the medical field. The grant allowed CRPM to assist a 32 year old woman suffering from "Ossifying Fibroma Tumour" in her lower jaw. The surgical medical team decided to resect the tumour immediately and place a custom-made laser-sintered titanium implant in the mouth of the patient (Benoit, 2016). The CT scans of the patient were converted into a 3D model, and this model of the bone and tumour was used as the input to plan the resection planes and design. The implant was fitted perfectly, and the models were printed in plastic, as seen in Figure 5(b), with the implant itself fabricated in titanium. The surgery was successfully carried out using cutting-edge guides (Benoit, 2016).

A USB with crank action was designed and printed using a EOSINT P machine at CRPM and was completely assembled, as seen in Figure 5(c) (CRPM-Facebook, 2016). A Titanium prosthetic limb was designed by Dr Lionel T Dean from De Montfort University, UK, and 3D printed at CRPM in 2017, and the Titanium prosthetic was also showcased during the annual RAPDASA conference in November 2017, as seen in Figure 5(d). Another case of myxoma of the midface, also funded by the Carl and Emily Fuchs Foundation, of a patient having a low quality of life because of rapid growth, used the medical data of the patient to produce a plastic/nylon 1:1 scale of the patient. The medical team was 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.

## 5.2 Vaal University of Technology

VUT (2017) is a university of technology located at the Vanderbijlpark in South Africa. The university has a technology station where excellent AM research activities are being carried out. The VUT's science and technology park at the Sebokeng campus has world-class in-house industrial grade

**Figure 5** Samples of recent AM technology research at the CUT CRPM Centre



**Notes:** (a) A case of a teenager born without ear canals who received new two ears; (b) Models 3D printed for a 32 years old woman suffering from "Ossifying Fibroma Tumour"; (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)

AM facilities for commercial, education and research purposes. The AM facilities at the VUT function as a service bureau that supports local industry and entrepreneurs and offers research support to both local and international researchers (De Beer, 2010). As of November 2017, the VUT at Sebokeng campus has more than ten high-end industrial grade AM machines such as EOSINT P 380, EOSINT P395, FORMIGA P 100, FORMIGA P 110, Voxeljet VX 1000 and the Voxeljet VX 500, etc. The introduction of AM technology to VUT started in 2011 with the establishment of the "I2P @ Lab" concept by a team of researchers. The main aim for the establishment of the I2P Lab is to serve as a platform for technology transfer and innovation for emerging advanced manufacturing technologies such as AM between academic institutions and industry.

Currently, VUT offers the highest resolution polymer laser sintering in SA, with a range of other AM technologies including fused deposition modelling (FDM), selective laser sintering (SLS), 3DP, etc. to manufacture prototypes and products. The VUT AM facility is funded by the Technology Innovation Agency (TIA). As part of the VUT plan to introduce AM Education, the I2P Lab is used to train and introduce students from high schools within the Sebokeng communities to acquire the fundamental knowledge about AM technology. Annually, the VUT AM facility organises a programme called "Engineering Week" to develop awareness within high school students by showcasing the benefits of AM technology through their world-class in-house facilities. Based on the primary data collected, between July 2016 and July 2017, 200 people were trained and introduced to the fundamentals of AM technologies using the entry-level desktop 3D printers at the I2P Lab. The gender of those trained during this period consisted of 90 males and 110 females. The students were first introduced to the fundamentals of AM, such as the operation of AM technologies, product development cycle and design techniques using 123D Autodesk beta software and latterly, they were exposed to the practical aspects



of AM/3DP technologies by converting their creative thinking into a physical final product using the AM facilities available.

The AM facilities at the VUT serve the industrial sector (i.e. manufacturing, aerospace, etc.) through daily production of 3D printed components. In 2017, almost 30 intern students were admitted to the VUT AM unit for a one-year internship programme with the aim to expose the interns to a range of AM technologies and education to gain quality knowledge of about these processes and get hands-on experience on both entry-level 3D printers and high-end industrial AM machines. According to [Campbell and De Beer \(2017\)](#), since the inception of I2P Lab at VUT, approximately 7500 students have been exposed to and utilised the AM facilities. [Campbell and De Beer \(2017\)](#) also recorded that the industrial engineering, and operation management undergraduate students at VUT used the I2P Lab for Production Engineering IV course in first semester of their degree. In recent times, some lecturers and students in the Department of Visual Arts and Design (specifically, Fine Arts option) have also taken advantage of the 3DP facilities for their final design printing.

### 5.3 North-West University

NWU is situated on the North-West Province of SA and recently established an “Additive Manufacturing Research Group” within the Faculty of Engineering and through this medium, various AM research activities are being carried out. As part of the strategy to make the AM research group at the university effective, a 3DP technology lab has been launched called “NWU Pukke 3DP centre” which is well-equipped with several entry-level desktop 3DPg machines for use by academics and students. The NWU 3DP centre also has high-end industrial grade AM machines at the university’s fabrication laboratory (FABLAB) also for use by the students and academics for design of prototypes, R&D, and for commercial purposes. As part of the recent development in the School of Mechanical and Nuclear Engineering, all of the mechanical engineering students have been encouraged to make prosthetics as part of their final year projects 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 Masters student at the School of Mechanical Engineering designed a prosthetic arm for a particular patient with the high-end industrial 3DP facilities at the University FabLab ([NWU, 2017](#)). Furthermore, as part of the plan to gradually integrate AM technology into the educational system at the university, the undergraduate students within mechanical engineering, industrial engineering and electrical and electronic engineering are using the 3DP centre to carry out their design assignments and unique projects that are related to design and manufacturing.

AM research activities at NWU are gradually expanding within the postgraduate degree programme as a doctoral student at the occupational hygiene research unit of the university is working on research entitled “The hazardous chemical substance exposure associated with additive manufacturing processes”. The research is expected to identify the health risks associated with all the manufacturing processes located at the CSIR, VUT, CUT and SU. Similarly, another doctoral student in development and management engineering

is currently working on research entitled “Framework for effective Additive Manufacturing education at South African universities”. The aim of this research is to investigate the impact of AM education and facilities at the selected SA universities and to develop a framework for effective AM education at these universities. Finally, two lecturers from the school of Mechanical Engineering are working on a research project entitled “Additive Manufacturing Material Characterization”, with the aim to determine the properties of various FDM materials which are usually used in 3DP. [Figure 6](#) shows a collage of some of the 3D printed components designed and manufactured by the engineering students.

### 5.4 Stellenbosch University

SU is a research-intensive university located in the town of Stellenbosch, SA. Over the years, SU has been 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 (RPD Lab) which is leading the SU effort to explore 3DP’s value in manufacturing, prototyping, architecture and medicine. SU students have used AM machines 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 3DP technology through the conversion of CT and MRI scan 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 visualising abnormalities such as tumours and birth defects ([Dimitrov, 2006](#)). The work at the RPD Lab has exposed many students across multiple disciplines to AM technology, not only engineering students. [Dimitrov \(2006\)](#) stresses that the scope of possible uses for AM across universities is only broadening as additional educational opportunities are uncovered. The importance of AM education at SU combines students’ involvement with industry partnerships and high-end AM technology equipment, which provides university–industry collaboration in AM technology research. In short, this has provided unprecedented education potential for SU students which allows them to gain hands-on-experience while working with industry partners ([Dimitrov, 2006](#)).

However, AM R&D at SU is on a small scale compared to other universities like CUT and VUT that have several high-end industrial grade AM machines. As part of the mission of SU to promote AM education/technology within the university system, an Idea 2 Product Lab was established in 2015 for manufacturing of on-demand 3D printed components. The

**Figure 6** Collage of some of the final 3D printed products designed by the engineering students using the NWU Pukke 3DP centre



new AM in-house facilities at the I2PLab aimed to bring AM technology to everyone (for instance, students, academic staff and the general public) by making it accessible and easy to learn for those who are new to the technology (I2P Lab, 2017). The I2PLab at SU is regarded as an open access facility for self-use CAD and 3DP which allows classes/groups to incorporate AM into courses at the university. Figure 7(a) shows some samples of 3D printed parts manufactured from the lab, and Figure 7(b) shows the four entry-level desktop 3D printers and 3D Scanner which is accessible to students for design project purposes.

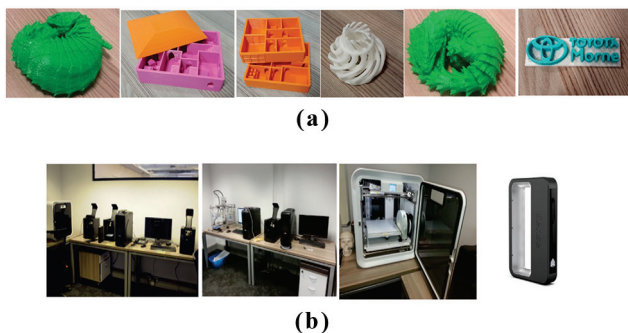
## 6. Sustainability of additive manufacturing from education perspective

The term “sustainability” is a varied concept in today’s world and is 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 organised by the USA National Science Foundation (NSF) entitled Frontiers of Additive Manufacturing Research and Education. Different stakeholders from the academia, industry and government were present at the workshop, sharing their ideas, innovations and knowledge relating to the frontiers of AM education, research and technology transfer (Huang and Leu, 2014). The report from the workshop summarises the current state, future potential gaps and needs for AM education with appropriate recommendations.

AM education and training is rapidly growing worldwide, most especially in the USA. 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 were identified by the stakeholders during the NSF workshop are as stated below (Huang and Leu, 2014):

- university–industry collaboration;
- technology transfer;
- education and training; and
- technology and research.

**Figure 7** Samples of finished 3D printed components and the AM in-house facilities at the I2P lab at SU



**Notes:** (a) A collage that shows some samples of 3D printed components; (b) some of the 3D printers and 3D scanner facilities

To sustain AM education, some of the barriers need to be properly addressed such as a lack of AM educational practitioners, cultural differences, acceptability of AM technology in universities, colleges and industry, vested interests and lack of imagination and innovation. Based on this, Bourell et al (2009) made certain recommendations that will help in overcoming the AM education limitations are as follows:

- prolong university courses on AM;
- provide education materials;
- create curriculum at technical colleges, undergraduate and postgraduate levels; and
- training program in AM with certification for industry practitioners.

## 7. The SWOT analysis

A SWOT analysis is a tool used to analyse the strengths, weaknesses, opportunities and threats in businesses, organisations and research. A SWOT analysis can be referred to as a framework to assist researchers to identify and prioritise research goals and can be used to further pinpoint the strategies of achieving the set goals (Ommami, 2011). The strengths and weaknesses are referred to as internal factors, whereas the opportunities and threats are the external factors. In this paper, a SWOT analysis is used to evaluate the present and future prospects of AM education and research activities at SA universities.

## 8. Conclusion

This paper presents a comprehensive insight into AM research activities within selected SA universities, thereby promoting AM education. The paper presents an up-to-date history of AM and future strategy specifically for SA. Further, it focusses on AM education and presents the global perspective and sustainability of it. One of the limitations of this paper is that the scope was limited to AM activities within selected SA universities and does not present the application of AM/3DP in education more generally. For SA Government to fully reap the enormous benefits from the huge investment they have made in AM technology to date, there is a need for more research activity to be undertaken. It is believed that various AM research activities across the major universities and colleges would serve as a platform to introduce AM education at SA’s universities. Recently, one initiative in particular has initiated the development of an AM course or curriculum for teaching the subject in SA universities. However, within the HEIs in SA, students are being exposed to AM education through courses related to design and manufacturing, especially within engineering degrees using in-house facilities, for example, at the I2P Labs or AM/3DP centres at these universities. More so, the authors recommend the inclusion of a full or short semester course in AM in SAs’ universities, which would serve as another great milestone for the SA AM industry, as well as introduction of a postgraduate programme (i.e. master’s degree) to increase AM research at these universities. An effective AM education and research at the universities will allow many students to develop interest in AM/3DP technology and to choose a career path in this technological discipline.

Table I The SWOT analysis to evaluate the present and future prospects of AM education and research activities

Strengths (S)	Weaknesses (W)
<p>The availability of high-end industrial AM machines at selected SA universities is a major advantage in promoting AM education and research in areas such as aerospace, medical, automobile and industrial designs</p> <p>Establishment of more I2P Labs in SA high schools, colleges and universities will enhance innovative and creative thinking among students and allow them to develop interest in STEM education</p> <p>In the coming years, RAPDASA will continue to serve as a right vehicle to promote AM activities in SA through the annual international conference and in creating global awareness</p> <p>Over the years, technology transfer has been playing a major role in the advancement of AM technology in SA universities and will continue to play an important role by providing both theoretical and practical knowledge to students, academia, entrepreneurs and industry professionals</p> <p><b>Opportunities</b></p> <p>An introduction of a postgraduate degree, for example “MSc or MEng” program in AM at major SA universities. This will serve as an opportunity to increase the number of professionals and expertise in the field of AM in SA</p> <p>Availability of large amounts of titanium in SA creates a great opportunity for production of medical implants and prosthetics. Likewise, SA platinum powder will enhance the jewellery industry in SA using AM technology</p> <p>Efficient university–industry collaboration would enhance AM research activities at the university and expose students and academics to AM education. Such collaboration could attract more internships for students and funding for the universities to conduct research in emerging areas of AM technology</p> <p>CUT indicated that a course in Mechanical Engineering was introduced to suit AM technology within the SA context. However, to enhance AM technology growth among students at SA universities, inclusion of a course or some topics in manufacturing courses related to AM in the undergraduate curriculum at the universities will serve as a good platform to educate people about AM technology and which will eventually promote a career path in AM field</p>	<p>To effectively promote AM education, there is a need for SA Government through DST, to create more centres of excellence and Research Chairs in AM at selected universities</p> <p>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 are needed in SA’s universities</p> <p>To encourage more postgraduate students and young researchers to attend annual RAPDASA conference and to get exposure to AM technology and research. RAPDASA conference committee should increase their scholarship to allow more people to attend</p> <p>More AM technology awareness needs to be done at SA HEIs to increase AM professionals/experts because a lack of AM personnel/educators is one of the factors identified for limiting the advancement of the technology in SA.</p> <p><b>Threats</b></p> <p>High cost of AM system and the materials, most especially the high-end industrial AM machines, is a threat to many HEIs and industry because it is delaying the adoption of AM technology across many universities.</p> <p>Lack of an effective framework for AM education at SA universities is another threat that needs to be addressed in the future</p> <p>For higher quality and advanced research in AM, consistent funding from NRF/DST and other funding bodies is needed for SA to compete globally in cutting-edge AM research.</p>

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