Additive manufacturing in South Africa: critical success factors

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Abstract

Despite the advances and significant benefits of additive manufacturing globally, Africa and several developing countries are lagging behind due to several adoption barriers. South Africa has nevertheless made significant gains in the area of additive manufacturing over the past three decades. The current study examines the critical success factors that have led to South Africa’s relative success in the field of additive manufacturing by overcoming the barriers. One of such success factors was the demonstration of visionary leadership and commitment to additive manufacturing through huge investments. The building of human capital through education and research in the area of additive manufacturing is another factor. The development of a strong collaboration between industry and research involving both local and international institutions represents another success factor in South Africa’s additive manufacturing growth. Lastly, a positive national culture that drives the adoption of new technologies which is defined by the display of low power distance, high individuality, masculinity, and lower uncertainty avoidance index is another success factor of additive manufacturing in South Africa.

1. Introduction

The constantly evolving nature of industries around the world has called for more innovative technologies and research in the areas of product design and manufacturing processes [1, 2]. This has become very important due to several factors, including the increasing demand for customization, the desire to gain a competitive advantage in the market, and the recent calls for more sustainable practices and processes in production to improve environmental performance [3, 4]. One such innovative technology that is gradually gaining popularity around the world is additive manufacturing (AM), also known colloquially as 3D printing [5, 6].

The AM technology is classified into different categories by ISO/ASTM 52900:2021 [7], according to their processing mechanisms. Based on the processing mechanism, each of the AM technology can print different material/s feedstock with different geometrical accuracy [8, 9]. For example, powder bed fusion technology is mainly used to produce 3D structures of intricate shapes with high geometrical precision for biomedical and engineering applications while directed energy deposition machines are mainly used to repair metal components for large-scale production [10]. Other AM systems such as sheet lamination and binder jetting are used to join different material/s feedstock for a specific industrial application (Table 1).

The global additive manufacturing market continues to expand, from 6 billion in 2016 to 13.78 billion dollars in 2020, with an estimated growth of more than $26 billion by 2022 [19, 20]. Additionally, Gerstle et al. [21] stated that 50% of all globally manufactured goods will be printed using additive manufacturing technology by 2060 if the current investment in additive manufacturing continues. This notable increase in growth and expansion in additive manufacturing is a result of the numerous potential economic, technical, and environmental benefits it offers compared to conventional manufacturing (casting, forging, sheet forming, extrusion, etc.) [8] in the production of parts intended for end-users [22]. This, among other things, includes freedom of design, which contributes to the lightweight consolidation of parts and integration of function parts [23, 24]. Other benefits include low-volume production and the facilitation of personalized and customized products, in addition to low-cost production and less dependence on expensive and dedicated tooling [25, 26]. Responsive production, shorter supply chains, democratization of production, reduction of the environmental
impact due to less waste production as well as increased preparedness for the digital revolution are other advantages of additive manufacturing [27]. Due to the versatility of the AM technology to produce customized 3D structures, it is one of the advanced manufacturing technology which is currently used to provide medical devices to fight the covid-19 pandemic [28, 29]. As covid-19 pandemic has disrupted the supply chain around the globe [30], AM technology has come to the fore as one of the most reliable technology to improve many medical devices due to its freedom of design [30]. The agility of the AM technology has been demonstrated by providing tailored medical devices for specific clinical application as opposed to the classical methods of manufacturing.

Despite these outstanding capabilities of AM technology for economic development, Africa is currently trailing behind some of the developed countries, such as America, which controls 36% of the market, followed by Asia with 28%, Europe with 26%. Africa and the rest of the world control only 19% of the additive manufacturing market share [31]. Several scholars agree that many countries and organizations have failed to take advantage of additive manufacturing due to economic, organizational, technological, and person-related barriers or inhibiting factors [32, 33, 34]. Specifically, Cotteleer [35] and Wu et al. [25] contend that future development of additive manufacturing is often hampered in several countries, especially those in developing countries, by high initial capital requirements for additive manufacturing machines and materials, intellectual property/privity issues, lack of human capital, tiny production runs and scalability constraints, production standards and requirements, regulatory uncertainty in different countries, as well as a lack of choice of materials. The resultant effect of these inhibitors, according to Sobota [36], is that the adoption of additive manufacturing in practical applications continues to lag behind projections, and components created through additive manufacturing continue to remain the exception rather than the rule.

Amid these challenges, South Africa has emerged as a key player in additive manufacturing, not only in Africa but in the world [37]. It has made significant advances in both the industrial market (medical, dentistry, aeronautical, and automotive) and the consumer market (home furnishings and entertainment) [38]. Assessing the maturity level of additive manufacturing applications in South Africa based on the technology readiness level (TRL) scale of 1–9 [39], reveal that in the area of tooling it is rated at (7–9), automotive (4–6), medical (5–7), and aviation is at (7–9). From the perspective of Ahuja et al. [40], the TRL evaluation demonstrates that the real production setting of South Africa’s capability in additive manufacturing applications is relatively advanced. Corroborating these findings, Alabi et al. [41] indicated that “South Africa has grown to become a leader in additive manufacturing and, although the adoption of the additive manufacturing 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.” Due to its relatively early adoption of additive manufacturing, South Africa has established itself as a model for other developing countries to follow [42]. This means that South Africa has been able to pursue better disparate strategies to overcome additive manufacturing barriers to ensure that the technology and its automation move into the mainstream. The questions are: what are the disparate strategies or critical success factors that have led to South Africa’s success in the field of additive manufacturing, and what are the valuable lessons that other developing countries, including those in Africa, facing similar challenges in additive manufacturing adoption can learn to inform their development strategies?

2. Methodology

To elucidate the critical success factors that make South Africa emerge as a leader in the AM industry; documents, and publications on the South African National Additive Manufacturing Roadmap (SANAMR) which is the foundation for the review were thoroughly analyzed. The publications and the relevant documents of famous authors that participate in the development of the South African National Additive Manufacturing Roadmap were thoroughly reviewed. The archives of RAPDASA (Rapid Product Development Association of South Africa) that focused on the South Africa National Additive Manufacturing Roadmap were thoroughly examined. The archives of Council for Scientific and Industrial Research (CSIR) were also checked for relevant documents on the SANAMR. Reviewing these initial foundational documents gives guidance on the type of precise search words that could be used to search other databases for additional information. The main search terms that were used were: Additive manufacturing, 3D printing, South Africa, technology adoption, diffusion of technology, collaboration between industry and research, Leadership, National culture, Human capital, Education and research, and Critical success factors. These terms were combined using the Boolean search operator “AND” to narrow the search results to specific output (eg. “Additive manufacturing” AND “3D printing” AND “South Africa”). The Boolean operator produces results that meet multiple criteria. Some relevant published documents were also accessed based on

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**Table 1. Classification of AM technology.**

| AM technologies | Type of machine | Printable materials | Mechanism of printing | Applications | Refs. |
|-----------------|-----------------|---------------------|-----------------------|--------------|-------|
| Powder bed fusion | Selective laser sintering Electron beam melting | Metallic feedstocks, but can also be used to print ceramics, polymers, and composite | Uses electron or laser beams to selectively build 3D objects | Use to produce high-value customized biomedical and engineering products. | [8, 12] |
| Directed energy deposition | Laser deposition laser engineered net shaping (LENS) | Used to print metallic feedstocks, but can be used to print ceramics, polymers | Using a laser beam to selectively build 3D objects. | Use to produce 3D objects for biomedical and engineering applications | [5, 13] |
| Sheet lamination | Laminated object manufacturing (LOM) Ultrasound additive manufacturing (UAM) | Metals, plastic, papers | Sheets of materials are joined one after the other either by adhesive, welding or thermal bonding | Can be used to produce 3D objects at a lower cost compared to other 3D printing technology | [5, 11] |
| Material extrusion | Fuse deposition modelling | Polymers, food, living cells | Material is drawn through a nozzle, heated, and deposited layer by layer. | It is commonly used to build inexpensive products for domestic and industrial applications. | [5, 14] |
| Material jetting | Drop-On Demand (DOD) PolyJet technology NanoParticle Jetting (NPJ) | Polymers, ceramics, composite, biologicals and hybrid | Printhead dispenses droplets of photosensitive material that solidifies, layer-by-layer under ultraviolet (UV) light. | It is commonly used to build inexpensive products for domestic and industrial applications. | [5, 15] |
| Binder jetting | Binder jetting | Metals, sands, polymers, ceramics and composites | A liquid binding agent is selectively deposited to join powder particles. | Production of casting patterns. | [16, 17] |
| Photopolymer vat | Stereolithography (SLA) Digital light processing (DLP), Carbon® Digital Light Synthesis (DLS) | Polymers | Selectively curing of photo-reactive polymers by using a laser, light or ultraviolet (UV). | Production of 3D objects for biomedical and engineering applications. | [5, 18] |
the Snowball method (locating relevant documents based on the reference list in relevant articles).

Through the Central University of Technology library search database selector, and other affiliated South African university libraries, the following are some of the electronic resources that were accessed: SAGE Research Methods, NETLAW, EBSCOHost, ASTM’s Digital Library, Clarivate Web of Science, Sabinet African Journals/SA e-Publications, Nexus: Current and Completed Research Projects, McGraw-Hill Access Engineering, Emerald, Taylor, and Francis Online. Google Scholar was also heavily used and the Advanced Scholar Search feature in Google Scholar was used to set specific criteria. To access publications that are current and relevant to the studies the period was set from 2000 to 2022 in Google Scholar. The libraries were used due to their large collection of data on the topic. The internet was used due to its limitless network of resources.

To ensure credibility, validity, and reliability only peer-reviewed published documents were used. The citation index was also used to examine the citation frequency of authors whose published documents were deemed credible to be included in the current review publication. The abstract and the conclusion of each article were first examined. The evaluation of the publications was based on the quality of the content, the relevance of the topic to the current review, the credential of the source’s authors, and the year of publication (from 2000 to 2022). Some relevant documents from previous decades were also consulted to establish foundational concepts that continue till today. It is worth mentioning that only published articles in English were used since the documents on SANAMR were written in English.

The exclusion and inclusion criteria used to select the relevant published documents for analyzing the critical success factors of South African AM’s outstanding performance are presented in Figure 1. The direct search of the relevant archives such as SANAMR documents, RAPDASA documents on the implementation and progress of SANAMR retrieved 211 documents. A general search of other available electronic resources output 182 articles, hence a total of 393 articles were initially identified for the studies. Due to the direct search approach, about 60 % of the publications from the general electronic resources were duplicates. After the duplicates were removed, 287 articles were left for analysis. The abstracts and conclusions of the 287 articles were reviewed for eligibility. 77 articles were excluded after reviewing the abstracts and the conclusions of the published documents. The 77 articles were excluded because after critically examining the abstracts and conclusions, the articles did not focus on the discussions of the critical success factors of AM in South Africa. 210 full-text articles were read and 58 were excluded. The 58 articles were excluded because they did not comprehensively focus on the implementation or progress of the SANAMR (Figure 1). Finally, 152 articles were used for analyzing the critical success factors that enable South Africa to emerge as a global force within the 3D printing industry.

3. An overview of South Africa’s additive manufacturing industry

South Africa’s path toward additive manufacturing began nearly a decade after the international community accepted the technology [42]. In 1991, South Africa received its first additive manufacturing system, a 3D Systems SLA 250, through the Council for Scientific and Industrial Research (CSIR), followed by the installation of two FDM 1500 machines, which were later upgraded to FDM 1650s. Five years later, a Technological university called CUT and the CSIR purchased and installed a Sanders Model Maker II, as well as SLA 250 and 500 machines [41]. By 1998, South Africa had grown its total number of additive machines to seven, with six placed in research institutions and institutions of higher learning.

The establishment of the Rapid Product Development Association of South Africa (RAPDASA) in 2000 sparked widespread interest in additive manufacturing, which has generated different research outputs in the form of projects and academic research over the years. According to De Beer [42], the additive manufacturing base in South Africa has served a broad and diverse range of application areas, including automotive work, industrial design models, jewellery masters, medical visualization, anthropological studies, low-volume tooling, architectural models and rapid manufacturing of functional parts.

Due to the government’s emphasis on collaborative research and development, major expenditures were made between 2014 and 2016 on additive manufacturing of titanium medical implants and aerospace components, as well as polymer additives in design [41]. According to Du Preez and De Beer [38], such investment has enabled South Africa to acquire world-class capabilities, positioning her well to participate in the rise of additive manufacturing in critical sectors like aerospace, medical equipment, and implants. These accomplishments align with South Africa’s National Additive Manufacturing Roadmap, which was launched in 2013 with the goal of empowering local businesses and industry sectors to become world leaders in selected areas of additive manufacturing.

The National Additive Manufacturing Roadmap served as a compass to direct the research, development, innovation, commercialization activities of all the players in the AM industry in South Africa. In an effort to realize this roadmap, an additive manufacturing Centre of Competence (CoC) was established to aid in the development, industrialization, and commercialization of technologies that are essential to building an internationally competitive manufacturing industry in South Africa [38]. The South African National Additive Manufacturing Roadmap which serves as the vehicle for achieving the AM development and commercialization was categorized into four groups:

**Qualification of AM parts for medical & aerospace applications**: The qualification process focused on the formulation of production standards and policy that would govern the AM industry (Manufacturing parts according to the international standards). Through the CoC, many IOS (International Organization for Standardization) standards have been obtained for manufacturing AM components for the medical and aerospace industry. For example, one of the CoC, Centre for Rapid Prototyping and Manufacturing (CRPM) at CUT received ISO 13485 certification for 3D printing of medical devices. It is the first CoC in South Africa and Africa to receive the ISO certification for Additive Manufacturing [43, 44].

**AM for Impact in the Traditional Manufacturing sectors**: The roadmap also focused on improving the efficiency of conventional manufacturing methods through tooling development using AM prototypes to enhance the manufacturing cycles. This section of the roadmap also focused on the refurbishment of previously un-serviced parts through powder deposition technology [45].

**SMME (Small, Medium and Micro Enterprises) Development**: The roadmap is aimed at developing AM based SMME industry. These AM based SMMEs would focus on using AM technology mainly in the creative arts industry (Making jewellery, artefacts, AM shoes etc) [38].

**New AM Materials and Technology**: The development of new AM systems and materials was part of the roadmap. The focus was to increase the material data based for the already existing AM systems and the new ones, to make the technology applicable for varied applications since one of the limitations of the widespread/adoption of the technology is the limited choice of printable materials. The roadmap also focused on developing new AM machines which lead to the Aeroswift project. The Aeroswift project is a collaboration between Aerosud, a leading provider of aviation manufacturing solutions, and the South African Council for Scientific and Industrial Research (CSIR) resulted in the development of Aeroswift, the world’s largest and fastest additive manufacturing system for titanium aircraft components [46].

The South African National Roadmap for AM has propelled the AM industry in South Africa with distinct achievements. As a result, South Africa’s additive manufacturing sector has grown at a rapid pace, from a single Stereo Lithography Apparatus 250 (SLA 250) in 1991 to 90 3D printing machines in 2001 [19]. According to Du Preez and De Beer [38], South Africa’s AM landscape and sales increased significantly between 2010 and 2015, from 200 to approximately 3500 additive manufacturing
machines at the high-end of the industry which represents an increase of 94.2%. Between 2015 and 2020 the country’s projected AM machines were 6381 which represents an increase of 45.1% (Figure 2). Based on the available data [37] it is projected that AM machines would reach approximately 9652 by 2025 and 12,923 by 2030 which represents an increase of 33.8% and 25.3% respectively (Figure 2). This means that South Africa’s AM landscape is projected to see significant growth in the future. Additionally, Campbell et al. [47] reported that around 48% of South African institutions of higher education have in-house additive manufacturing capabilities. In sum, South Africa has achieved great strides in the field of additive manufacturing, making the future of the industry extremely bright in comparison to that of other African countries.

4. Critical success factors of South Africa’s additive manufacturing

4.1. Leadership and investment in additive manufacturing

Adopting new technology, whether at the national or organizational level, is far from simple and presents numerous problems, such as employee acceptability and adoption [48]. Technology acceptance model (TAM) is one of the most frequently utilized models for explaining technology acceptance. It was the first model to assert that psychological factors, such as perceived usefulness and perceived ease of use, play a significant role in determining a new technology’s adoption and usage. According to Schepers et al. [49], these factors are significantly
influenced by leadership. Leadership is thus an essential factor in the adoption and diffusion of technologies at all levels. In line with this, Dintoe [50] contends that strategic leadership is needed to create a paradigm shift in planned, organized, and managed systems for transformational change in the adoption of new technologies. Similarly, Koziol-Nadolna [51] echoes that success in technological adoption depends on the leader’s ability to effectively communicate clearly the set vision or direction and the provision of the resources needed to achieve it.

In the context of South Africa, additive manufacturing could not be successful without the import of strong and strategic leadership both at the national and organizational levels. For example, President Cyril Ramaphosa established the Presidential Commission on the Fourth Industrial Revolution (PC4IR) in 2019 to develop an integrated country strategy and plan to respond to 4IR, including detailed interventions to be carried out in achieving global competitiveness of the key economic sectors (agriculture, finance, mining, manufacturing, ICT, and Science, Technology, and Innovation) [52]. Setting the tone for the 4IR, which also comprises additive manufacturing, South Africa’s President, Cyril Ramaphosa indicated that “unless we adapt, unless we understand the nature of the profound change that is reshaping our world, and unless we readily embrace the opportunities it presents, the promise of our nation’s birth will forever remain unfulfilled” [52]. The president’s role as the head of the commission describes the commitment and the direction of the government and leadership towards the 4IR and, by extension, additive manufacturing as a long-term development strategy.

Prior to this, the government of South Africa has shown leadership in providing directions and resources toward additive manufacturing adoption and development. According to Alabi et al. [41], the government of the South of Africa has been investing in additive manufacturing since the 1990s, and between 2014 and 2016, a total amount of 358 million Rand (EUR 22 million) has been invested. Additionally, Williams [53] asserts that an additional amount of 30.7 million Rand (almost EUR 2 million) has been set aside for the development of additive manufacturing in South Africa. As part of the South African government’s strategy to gain a competitive advantage in 3D printing and the creation of jobs, the Industrial Development Corporation (IDC) began investing R17 million (the equivalent of about $1.2 million) in Metal Heart, a startup that manufactures metal 3D printers for production [54]. Aerossift, which aims to build the world’s largest and fastest additive manufacturing system to 3D print titanium aircraft parts from powder, is yet another demonstration of the government’s commitment to additive manufacturing [55]. The South African government has demonstrated its commitment to realizing additive manufacturing and increasing the country’s involvement in Industry 4.0 through the previously mentioned government-backed initiatives and Metal Heart’s recent purchase of an SLM Solutions SLM 280 system to help with component production in the tooling industry and prototypes for other industries. The provision of effective leadership at the governmental level in terms of strategic direction and the provision of resources in terms of funding, as well as the technical direction by the Department of Science and Technology, CSIR, and other research institutions, has created a solid additive manufacturing infrastructure for the growth and commercialization of 3D products. According to Mashambanhaka [56], the effect of this is that various well-known international 3D printer makers and suppliers have built up a base in South Africa. This has led to reseller programs and distributorship partnerships with several local South African enterprises. As a result, there are already more than fifteen companies in South Africa that specialize in 3D printing services. In summation, Williams et al. [57] stated that South Africa’s large investments in AM capabilities positioned the country to participate in AM subsectors with strong growth potential, including aerospace applications and medical devices and implants.

4.2. The building of human capital through education and research

Overcoming the barrier of lack of human resources in the area of additive manufacturing [58] has been one of the critical success factors of South Africa’s additive manufacturing success story. South Africa realized that building human capital was very essential to the additive manufacturing industry’s growth and, as such supported research and
programs of research institutions and universities. According to Campbell et al. [47], additive manufacturing-related research is well-represented at all of South Africa’s major universities. They further estimate that around 48% of all universities in South Africa now have their own AM facilities. The strategic development focus of additive manufacturing at universities was to build human resource competencies at various levels with the goal of building human capital to support AM industries in the country.

In an effort to harness the different additive manufacturing competencies of human resources, different universities in South Africa have been equipped to build capacity in different and yet complementary aspects of additive manufacturing. For instance, while the CUT, located in Free State, has the widest range of AM machines in the country, the most in-depth knowledge of how to use and research the technology (physics, materials science, mechanical engineering, etc.), innovates and commercialized manufactured products [38]. On the other hand, Stellenbosch University, located in the Western Cape, has a lot of experience in binder jetting with applications in the manufacturing, medical, and architectural fields. Additionally, while the focus and competency of the National Laser Center located in Gauteng province, is focused on powder-blown AM machines, Vaal University of Technology (VUT) in Gauteng Province has expertise in studying the metallurgy of SLM parts [38]. In addition to focusing on powder processing, with a history of great expertise in health and safety, the North-West University located in Northwest Province has been training tooling engineers across the country. Lastly, Aerosud, also located in Gauteng, focuses on designing and manufacturing for the aviation industry using additive manufacturing [46].

It is evident that, the different additive manufacturing machines have been placed in different provinces and towns to ensure the human capital buildup is well distributed throughout the country and not localized. This enabled special competencies in specific areas of additive manufacturing to be built across the country, which is expected to spill over to different industries. The impact of additive manufacturing knowledge and expertise for universities and research institutions has resulted in the establishment of several new additive manufacturing applications and related businesses.

4.3. Collaboration between industry and research

The strong level of collaboration between industry and research institutions over the years has been another critical factor in the growth and expansion of additive manufacturing in South Africa [22, 38]. This collaboration is designed to help in solving problems on the shop floors through the provision of innovative solutions. Through research and collaboration with industry, South Africa’s additive manufacturing is using titanium to replace other metals used in manufacturing aeronautic and military components due to its strength-to-weight ratio. An example is a collaboration between the Centre for Rapid Prototyping and Manufacturing (CRPM) of CUT and the Aeroswift project hosted at the CSIR National Laser Centre, which resulted in the printing of 3D titanium aircraft parts manufactured for both Boeing and Airbus [57].

In the medical and dental fields, the strong collaboration between industry and research is fostering the growth and development of new AM medical products. For instance, additive manufacturing has enhanced the printing of synthetic implants and different prosthetics, in addition to bioprinting and tissue engineering, which has consequently reduced the average of five years of waiting among the majority of state-funded hospitals for prostheses to three years [59]. According to De beer et al. [60], the collaboration between CUT and the medical industry has resulted in the development of several products, including patient-specific X-ray shielding masks, customised manufacture of medical prosthetics, elbow implants, cranial implants produced directly from titanium alloys using Selective Laser Melting, etc. [61]. The dental field has also benefited greatly from research and industrial partnerships since new alloys have been developed that have provided the most cost-effective dental solutions for dental patients [62]. More than 1000 patients have been helped since 2015, thanks to the help of public and private hospitals, the expertise of the CRPM, and funding from partners including The Carl and Emily Fuchs Foundation and the Department of Science and Innovation (DSI) [44]. This collaboration, besides providing unique and innovative products for different industries, also forms the foundation for the growth and expansion of the additive manufacturing industry in South Africa as the need for new products and innovation continues to grow.

The continuous collaboration between research institutions such as Val University and the shoe manufacturing industry has resulted in the conceptualization of entirely new products, especially in relation to molding of shoe lasts and soles [44]. Through research collaboration between Val University and the shoe manufacturing industry, the printing of shoes is shaping the use of acrylic plastic powder and colored chemical binder. Already, Nike and New Balance offer high-end football and track shoes with cleat plates that are made by AM [44]. The current footwear industry in South Africa is valued at R5 billion and is predicted to double in size over the next five years [44]. Additive manufacturing presents a great opportunity for the traditional manufacturing industry. Thus, through collaboration with research and traditional footwear manufacturing, additive manufacturing is expanding and growing through industrial collaborations.

The building and strengthening of international links and collaboration is another key factor that has helped South Africa to build capacity in terms of human capital, which has ultimately contributed to the significant growth of the additive manufacturing industry in South Africa. For instance, the CUT located in Free State has a joint partnership with EOS (Electro-Optical System) eManufacturing program, and Stellenbosch University (SU) has a formal agreement with Fraunhofer to establish a Joint Lab [47]. This international collaboration affords employees of these research institutions the opportunity to benefit from the training and capacity building that improves their competencies in additive manufacturing. In addition, new trends and best practices are also shared, which has a spillover effect on South Africa’s additive manufacturing industry.

4.4. Positive national culture

Nationality culture describes the set of collective beliefs and values that distinguish people of one nationality from those of another [63]. The Hofstede [64] cultural dimension is one of the most popular frameworks for analyzing the cultures of countries around the world. The Hofstede cultural dimension comprises four main dimensions, and include power distance, uncertainty avoidance, individualism/collectivism, and masculinity/femininity [63].

Power distance, therefore, refers to the degree to which people perceive an equal distribution of power in a society [63]. Countries with a high-power distance index are termed as having high power distance cultures and vice-versa. On the other hand, low power distance cultures tend to be defined by equality among members, decentralization of responsibilities, democratic leadership, and limited dependence on bosses. South Africa has a power distance of 59 [65], which means that it slightly leans towards a lower power distance. This implies that unlike high power distance cultures, which, according to Iñárritu [66] resist the adoption of innovative technologies, South Africa, on the contrary, per its power distance, is relatively adaptive to current technologies like additive manufacturing. This is so because the highly decentralized systems that define low power distance foster autonomy and flexibility, which facilitates adoption of new technologies. Thus, the low power distance culture that defines South Africa has contributed to the high penetration of additive manufacturing in several sectors of the economy.

Uncertainty avoidance is another dimension of national culture, which is the extent to which a society feels insecure when faced with uncertainty or the unknown. According to Hofstede [67], while high uncertainty avoidance societies are afraid of the unknown and thus avoid ambiguity or risk as much as possible, low uncertainty societies are not
afraid of the unknown and thus can take risks. South Africa has an uncertainty avoidance index of 49 [65], which implies that it slightly leans towards lower uncertainty avoidance. Thus, unlike high uncertainty avoidance cultures, which, according to Eseonu and Egbue [68] are prone to resisting change and innovation and unwillingness to invest the resources needed, lower uncertainty avoidance cultures, such as South Africa, tend to support risk-taking. This is evidenced in the high financial investment from the government in additive manufacturing, which serves as an encouragement for institutions and individuals to take additive manufacturing adoption risk.

Individualism, which is when individuals are integrated into groups and the extent to which societies seek and protect their own interests over the common goal of society, in addition to having a great deal of personal freedom and autonomy, is another measure of the national culture [67]. Accordingly, while societies with a low individualism index tend to display the interests of each other in a group in exchange for loyalty, and they are characterized by limited freedom and independence, high individualism index societies demonstrate the contrary [59]. With a high individualism index of 65 [65], South Africa demonstrates a culture that highly embraces innovation and would embrace additive manufacturing because the culture supports freedom and independence to make one’s own choices [63].

Masculinity is the last dimension of Hofstede’s cultural dimension, and it refers to the extent to which a society is dominated by masculine values as opposed to feminine values [63]. According to Hofstede [67], South Africa has a masculinity index and this makes society pay attention to ambition, innovation, heroism, competition, performance, and success, which are emphasized throughout the educational process and in the workplace as a whole [70]. As a result of this, countries with high masculinity scores such as South Africa are more likely to employ 3D printing technology in order to stay on top of their game in their respective industries. This argument implies that they intend to be ambitious and allocate more of their resources to innovative solutions.

In summary, Hofstede’s cultural dimensions show that South Africa’s national culture, which is characterized by a low power distance index and high individuality, masculinity index, and lower uncertainty avoidance index, stimulates the adoption of 3D printing technology in the country. This is supported by the fact that this culture facilitates risk-taking, independence, flexibility, a willingness to change, goal-setting, and assertiveness, which are critical in the adoption of technologies such as 3D printing [64, 71].

5. Current challenges and the way forward

Despite the remarkable success demonstrated by the South African AM industry and other notable advanced countries [72], is worth pointing out that numerous manufacturing challenges confront the AM industry which must be overcome to move the technology to the next level. However, due to the effective AM roadmap established in South Africa, the ongoing multidisciplinary and interdisciplinary collaborative AM research between the industry and academia, and the positive built national culture it is expected that these challenges would be overcome to move the AM technology to the next level. First, the material data based on AM processing is very low. There is ongoing research on developing new materials for AM processes at several South African research hubs [73, 74, 75] and in other parts of the world [72, 76], to increase the material data based for AM processes. However, due to the newness of the technology and the development of the new materials, the relationships between the printing processes and the resulting material properties have just begun to be characterized, hence the confidence in 3D printed components for structural applications is low [29]. This is expected because confidence in technology and products are developed after the information on the total safety of the product are available and the product has been used for a long period of time, and there are significant practical data to validate the numerical and analytical models [77]. The heterogeneity in the AM equipment and process parameters used to produce 3D structures is another challenge, hence the quality of 3D printed components are determined by the specific 3D printing machine and the process parameters [78]. As AM technology is progressing towards the era of multi-material manufacturing, issues of weak interfacial bonding between different materials, diffusion at the interface boundaries, microstructure, and mechanical properties begin to emerge [79, 80]. The presence of unmelted powder particles at the fusion zones of AM-built components, issues of residual stress, porosities, delamination, etc., which have a decisive effect on the mechanical properties of AM-built parts need to be solved. Han and Lee [79] stated that in addition to overcoming the current technical challenge and developing confidence in the structural integrity of AM components there is a need for a fundamental scientific understanding of materials science, reaction kinetics, mechanics, and the thermophysical difference between the different materials that are being developed for AM process which is the research focus among several collaborators in South Africa AM ecosystem [37, 75, 76]. A thorough understanding of the materials’ properties would enhance proper interpretation of numerical and empirical results which would aid in overcoming the current challenges and improve confidence in AM build parts as the practical data to validate the behavior of AM components is becoming available. Apart from the emerging multi-material additive manufacturing process, issues of hybrid manufacturing begin to emerge in the AM industry recently. There are research centers within the South African AM ecosystem that are focusing on hybrid additive manufacturing [81]. Different advanced manufacturing technologies are combined with AM technologies to produce 3D structures for industrial applications. This emerging trend of hybrid manufacturing is seen as the perfect solution for producing 3D structures with tailored geometrical, technical, and functional properties for specific industrial applications [81, 82]. AM technology had demonstrated its resilience during the zenith of the Covid-19 pandemic when CAD files were transmitted via the internet to print components for manufacturing firms, spare parts/improved parts, personal protective equipment for hospitals, etc. when the global supply chain was destructed due to lockdowns in several parts of the world [83]. This has fueled the already intense research on solving the current challenges to make AM as one of the main manufacturing routes for the next generation.

6. Conclusion

South Africa has over the past three decades demonstrated growth and leadership in additive manufacturing. This success came through the adoption of the South Africa National Additive Manufacturing Roadmap, which enabled her not only to overcome the additive manufacturing adoption barriers but also drive significant growth and expansion of the additive manufacturing industry. CoC was the strategic vehicle that propel the upward trajectory of the AM industry in South Africa. Multi-disciplinary and interdisciplinary collaborative research, a positive national culture, and visionary leadership were some of the critical success factors that enable South Africa to become a leader in the AM industry on the African continent and the rest of the world. There are current challenges that are the central research focus in the South African AM ecosystem. The current collaborative research is focused on solving the heterogeneity in the material properties to build confidence in AM 3D structures. The emerging multi-material additive manufacturing and hybrid manufacturing have also attracted the interest of some of the research hubs in the South African AM research community. With the existing effective roadmap, it is expected that these current challenges would be solved to move the AM technology to the next level.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.
