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Can university-industry-government collaborations drive a 3D printing revolution in Africa? A triple helix model of technological leapfrogging in additive manufacturing

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ABSTRACT

The protracted disruption of Covid-19 pandemic on global supply chains has renewed calls for a new model of manufacturing that removes the need for centralised high-volume production and large inventory stocking. Drawing ideas from the Triple Helix model of university-industry-government innovation, this paper analyses the prospects for a 3D manufacturing revolution in Africa, a continent which was was disproportionately affected in the rounds of international border restrictions imposed in response to the Omicron variant of the virus. Taking a conceptual approach supported with case illustrations, the paper reviews the evolution of 3D printing technologies, the disruptive impact they have had on the traditional supply chain and the global expansion of the 3D printing market. Highlighting the favourable conditions for technological leapfrogging within the African context, the paper proposes a new integrative framework that explains how the emergence of new hybrid organisations from the Triple Helix can drive a promising manufacturing future for the continent -with small and medium enterprises playing a key role.

1. Introduction

The advent of 3D printing, a fabrication process by which a three-dimensional object is built (printed) by adding layers after layers of a particular substance across a cross-section of slices, has brought a new wave of optimism and enthusiasm about the prospect of Africa's economic miracle [1,2]. Commentators argue that this new disruptive technology, one of the main technological innovations driving the fourth industrial revolution, presents significant opportunities for technological leapfrogging in African countries [3]; (Infomineo, 2020). However, we know very little about how Africa could catch up and potentially leapfrog developed countries to play a leading role in the unfolding 3D printing revolution. Mirroring an emerging trend in South Africa, technology practitioners, consultants, and researchers alike, assert that, 3D technology is the new big technology that could be leveraged to support the emerging manufacturing industries in Africa, and in turn improve livelihoods (Scott, 2015; Davis College Akilah, 2016) and address recent challenges such as Covid-19 pandemic [4]. Yet, researchers are yet to pay sufficient attention to this Industry 4.0 technology, in order to deepen our understanding of the social, cultural, and technological context within which 3D could serve as an engine of economic growth on the continent [5].

Beyond descriptive and anedoctal narratives, we integrate ideas from the theory of technological leapfrogging and the triple helix model to develop an integrative model that could serve as an organising framework for exploring and exploiting the potentialities and limits of 3D printing in Africa. Thus, this paper addresses one main research question: In what ways can synergy and collaboration among university, industry and government sectors drive a manufacturing leapfrogging via 3D printing in Africa? In line with this, we focus on the opportunities for African countries to take advantage of the disruptive impact of 3D printing to the global supply and value chains and thereby launch a new era of industrial development on the continent. This is also especially pertinent within the context of Covid-19 pandemic, in which successive strains of the virus have precipitated protracted disruption of global supply chains, and thereby accelerating the adoption of alternative production models such as 3D printing. We therefore argue that the economies of one and de-centralisation of manufacturing production precipitated by 3D printing revolution introduce new rules of competition that are more advantageous to African and developing countries. Furthermore, as developed countries are relatively locked in the older technologies, African countries can have a fresh, if not a head, start in the fourth industrial revolution. However, in order to realise these ambitions, university, industry and government stakeholders must work in

Abbreviations: 3D printing, Additive manufacturing; Technological leapfrogging, Triple helix; Africa, Economies of one.

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dynamic synergy.

We contribute to the existing literature on 3D printing and augment the conceptual development of its benefits and factors facilitating (or impeding) its development by building on the triple helix and technological leapfrogging literatures. This enables us to extend understanding on the context within which 3D revolution could take place in Africa, a context characterised by underdeveloped markets and institutions. Our framework does not only advance a comprehensive and integrated view of 3D printing in Africa, it complements current theories on technological leapfrogging and advances our understanding of the potentialities of the technology in several ways. Firstly, we offer an alternative lens to exploring the evolution and diffusion of a disruptive innovation in contexts of developing markets and institutions. Secondly, we explain how these outcomes may lead to the identification of opportunities for innovation in additive manufacturing constructed through the proactive engagement and interaction of the three institutional spheres of university, industry, and government. Thirdly, we note the limitation of 3D printing initiatives to offer some guidelines and highlight key areas in which African universities, industry actors and governments can contribute to the development and growth of the market for 3D printing in Africa. We also highlight some practical and policy implications for the three institutional spheres: African universities need to re-invent and re-position themselves as entrepreneurial universities by embracing the Third Mission of economic development; industry stakeholders need to be more proactive and intentional in harnessing the research capabilities of universities for better productivity and competitiveness; and government need to be more strategic and targeted in its use of policy instruments to stimulate and grow the market.

The rest of the paper is organised as follows: first, we review the emergence of 3D technologies and the defining features and characteristics that have accounted for disruption of the global supply chain. Then we draw ideas from the triple helix model to examine the emergence of hybrid entities – universities, industries and government - in additive manufacturing. This is followed by case illustrations, where we discuss the contributions of universities, industry and government sectors to the development of 3D printing in South Africa and Kenya. We also highlight the key limitations of the paper. Next, we present a new integrated model linking together the triple helix, the conditions for technological leapfrogging in 3D printing and the process of 3D revolution in Africa. Finally, we bring all the insights together in the discussion and conclusion, with recommendations for future research agenda in additive manufacturing.

2. Literature review

2.1. 3D printing and the disruption of technological trajectories

3D printing is an additive manufacturing or fabrication process in which a three-dimensional object is built (printed) by adding layers after layers of a particular substance across a cross-section of slices [1,2]. The term "additive" distinguishes this process from the subtractive process in which an object is carved out of a block of raw materials, or the moulding process through which a molten material is cast into a solid form [6]. The stages involved in 3D printing include creation of a computer-assisted digital model of the object to the printed, followed by the decomposition of the model into successive layers that are printed one at a time. Scholars have identified three phases in the evolution of 3D printing technologies. The first, characterised by applications in rapid prototyping, involves the creation of plastic models of objects [6]. Here, architects, artists and product designers predominantly used them in rapid prototyping to create mock-ups of new designs [1]. The next phase, which began in the mid 1990s, was the phase of rapid tooling. Here, heat resistant polymers and metal alloys were used to produce customised tools within hours and at much cheaper costs when compared with the traditional subtractive manufacturing method [6]. The third and current phase took hold in the 2010s, and it is described as direct digital manufacturing (DDM), that is, a production process that is entirely based on digital interfaces using computer-assisted-design (CAD) models, without the need for casts or moulds. This phase incorporates the emergence of home fabrication [1], although other scholars have suggested that home fabrication should be recognised as a distinct, fourth, phase of 3D printing [6]. In between direct digital manufacturing and home fabrication, the industry has seen the emergence of local fabrication, spearheaded by digital 3D printing service providers. Overall, 3D service providers can be categorised into four groups: consumer 3D printing services; enterprise 3D printing services; 3D printing equipment and material producers; and 3D printing equipment and material distributors [7].

The emergence of 3D printing is having a major disruptive impact of global manufacturing and supply chains. The disruptive impacts can be summed up in terms of the observation that 3D printing has replaced the economies of scale that underpin traditional manufacturing with the "economies of one" that is driving 3D printing [8,9]. This has significant implications in three key areas. Firstly, it removes the need for centralised high volume production associated with traditional manufacturing. Instead, both materials and labour are sourced locally, where production takes place in closer proximity to customers and end-users. The hyperflexibility of 3D printing provides for options for manufacturers on raw materials that can be sourced locally. 3D printing allows for the use of materials such as sand, powder polymers, ceramics, wax and various composite materials [10]. Secondly, 3D printing eliminates the need for large inventory stocking, instead supporting end-user customisation and direct interaction between the local consumer and producer [9]. Because items can be produced fairly quickly on demand, there is no need for excessive inventory stocking in response to uncertain demand-the so-called "Bullwhip Effect" [8]. This gives the room for producers to postpone manufacturing to the latter stages of the delivery process, thereby reducing high shortage costs and practically eliminating the risk of obsolescence [11]. It also provides the opportunities for the emergence and contributions of "prosumers", that is consumers who are able to produce items from their homes [12]. Finally, the economies of one create new rules of competition, in a way similar to how the industrial revolution was a game changer against the local artisan [9]. Traditional manufacturing, under the design-build-deliver model, relies on reducing or eliminating variation in design to enable cost-effective production of parts at high volume. 3D printing flips this design for manufacturing model with a manufacturing for design. It changes the nature of design by unleashing the creativity of designers for competitive advantage; increases the interactivity between the design and production processes; and it gradually replaces globalisation with localisation processes in the manufacturing sector. Moreover, being part of the cluster of Industry 4.0 technologies, 3D printing is primed for integration with other Industry 4.0 technologies such as Blockchain, which provides digital solution to organising and securing data generated from end-to-end 3D printing processes [13].

The opportunities heralded by 3D printing is especially pertinent and relevant within the context of the protracted disruption of global value chains precipitated by successive variants of Covid-19 virus. In the first wave of the pandemic, borders and ports were shut down, forcing closures of businesses affected by the severe disruption. In the latest wave of the Omicron variant, African countries have been disproportionately affected, as Western countries in particular shut down their borders and ports to African countries. The current challenge can be an auspicious opportunity to accelerate the adoption of 3D printing on the continent.

The disruptive potential of 3D printing has other wide-ranging implications for both developed and developing countries. For developed countries, it increasingly reduces the need for multinationals to locate production overseas, where they can access cheaper raw materials and cheaper labour required for competitive advantage. Instead, it provides the opportunities for companies to decentralise production and relocate closer to major markets, including their home countries in many cases [14]. For developing countries, including African countries, this disruption provides a range of opportunities. First, at the micro level, it can shift the dynamics in favour of small and micro enterprises and artisans who are in closer proximity to consumers and can now harness the economies of one to drive a manufacturing revolution on the continent. They have the potential to unleash their creative ingenuity to create customised products and thus achieve competitive advantage [15]. Secondly, at the macro-level, the disruption precipitated by 3D printing is an auspicious opportunity for African countries to leapfrog developed countries in manufacturing. Compared with developed countries, African countries are not locked in the old technologies. We argue that a full switch to, and focus on, 3D printing could be not only relatively easier for African countries, it also has the potential to improve their competitiveness and capability development. In the next section, we explore in more detail the conditions necessary for technological leapfrogging to take place, and their implications for a 3D revolution in Africa.

2.2. Conditions for technological leapfrogging

Leapfrogging is the process by which a late-starter country, learning from past experiences and mistakes of developed countries, is able to catch up or bypass the intermediate stages of technological development to implement a more efficient and sustainable technology for production of goods and services [16,17]. This can be in terms of catching up in situations where technological change process is slow, or skipping the intermediate stages of the development in the context of rapidly changing technology [18]. Ancillary to the concept of leapfrogging is the idea of technological lock-in, a condition by which otherwise inferior and/or old technologies continue to dominate the market. This condition has been explained in terms of accumulated institutional rigidities associated with successful technologies in developed countries [19]. It has also been analysed from the lens of technology paradigms, and how the shared mental frames within the community of practice encourages incremental improvements, rather than discontinuous radical leaps, along certain trajectories [20].

Increasing returns, technological paradigms, and accumulated institutional rigidities account for technological lock-in in many developed countries (Arthur, 1991). Such lock-ins impede the emergence and potential uptake of new technologies and radical innovations in developed countries (Le Floc'h et al., 2012; Oberling et al., 2012). In turn, this presents unique opportunities for latecomer countries, not only to catch up, but also bypass developed countries and attain leadership in certain technologies. Brezis, Krugman and Tsiddon [19] identified four conditions that must hold if the introduction of a new technology is to lead to leapfrogging: i) there must be a large difference in wage costs between the leading nation and the challenging nation; ii) the new technology must appear to experienced producers as unproductive, especially at the initial stages of development; iii) experience in the old technology should be less useful and therefore less transferable to the new technology; iv) the new technology must offer substantial improvement in productivity and efficiency, relative to the old.

In line with the model set out by Brezis, Krugman and Tsiddon [19]; we argue that the profile of most African countries and the disruptive characteristics of 3D printing, fit the conditions for technological leapfrogging. First, there is a huge gap between the wage profile of developed countries and those of African nations. For example, according to the latest estimates, the average annual income in Nigeria is $2,030, compared with $65,850 in the United States (WorldData.Info, 2021). Furthermore, as highlighted in the previous section, while the development of 3D printing began in the 1980s, it caught on rather slowly because manufacturing companies considered it relatively unproductive and less profitable. In addition, as the trajectory of 3D printing is discontinuous rather than incremental, relative to traditional manufacturing, the knowledge experience in the older subtractive manufacturing is less relevant and less transferable to 3D printing. With regard to the fourth condition, the growing body of evidence indicate that additive manufacturing offer substantial improvement in efficiency and productivity, not least with its waste cutting characteristics and cheaper technology. However, in order for these conditions to be harnessed for actual outcomes, African countries must embrace a synergistic collaborative approach bringing together stakeholders from a whole spectrum of backgrounds.

This framework to explain and identify implications and opportunities for the hybrid organisational entity emanating from dynamic interactions between African universities, industry actors and governments (see Fig. 1) to drive a 3D manufacturing revolution in Africa.

In particular, we argue that, in order to drive a 3D printing revolution in Africa, universities, industry actors and governments may need to work in synergy in order to achieve the combinations of the four conditions that must hold to drive the leapfrogging process. Organised under the rubrics of the triple helix model of innovation framework, we delineate how an orchestrated interaction between the three institutional spheres of university, industry, and government, through their boundary spanning activities could drive and harness the conditions necessary to leverage the opportunities and potentialities for Africa's leapfrogging in 3D printing.

2.3. Leveraging triple helix model of innovation for 3D leapfrogging

The triple helix model of innovation has emerged as a significant heuristic framework for the production of knowledge for economic development. Advocating strategic interactions among previously distinct and often disconnected institutional domains of university, industry and government, provides context for the production of new knowledge, technologies, and ideas that drive innovation [21–23]. Emphasis on these institutional interactions has led to the emergence of an integrative, boundary-spanning institutional arrangements in which "industry operates in the triple helix as the locus of production; government as the source of contractual relations that guarantee stable interactions and exchange; (and) the university as a source of new knowledge and technology, the generative principle of knowledge-based economies" ([24]; pp. 295). The Triple Helix is thus characterised by the emergence of hybrid organisations at overlapping institutional spheres (Sarpong et al., 2017); [25].

The central thesis of the triple helix model is that a transformative interaction among university, industry and government is essential to driving innovation in a knowledge-based society [26,27]. The industry and government sectors have always been recognised as primary institutional spheres in the industrial society-the first as the locus of production, the second as the source and custodian of contractual relations necessary for economic activities to take place [24]. In African countries, tech hubs and DIY labs are exerting increasing influence as sites of knowledge production, challenging and invigorating traditional universities in the process [28]. The technical capabilities of these tech hubs need to be matched with better, innovative business models necessary for them to grow, internationalise and make stronger impact as creators of economic, social and environmental values [29]. Universities, as the third institutional sphere, can therefore play a key role as conduits and channels of international knowledge spill-overs, especially when they specialise in specific fields [30]. Universities can also drive regional knowledge spillovers through R&D collaborations with SMEs which are in social and geographical proximity [31]. The triple helix model of innovation assumes fluid boundaries among the three primary institutional spheres, and emphasizes the integration of their capabilities to boost national innovative activities and technology development (Leydesdorff, 2000; Brännback et al., 2008).

Etzkowitz [24] identified four stages that characterise the emergence of the Triple Helix. These include internal transformation in each of the helices; influence of one helix upon another; creation of a new overlay of trilateral networks and organisations from the interaction among the three helices; and a recursive effect of Triple Helix networks both on the

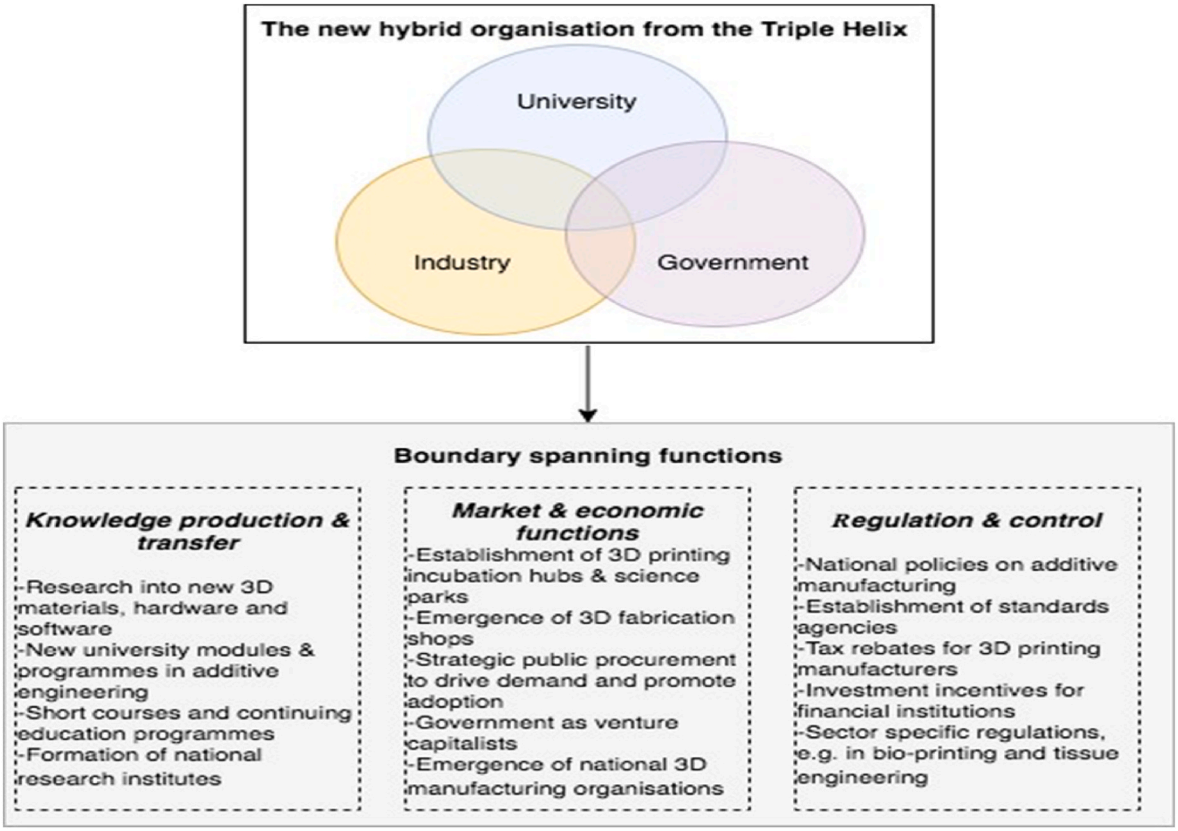

Fig. 1. Boundary spanning functions of 3D hybrid organisation.

internal system and on the larger society. We now elaborate on each of these four stages, within the context of 3D printing.

Internal transformation of the helices refers to the changes that are taking place within each of the three institutional spheres, where they each embrace new functions, activities and processes, in addition to the ones traditionally associated with them. The university sector has emerged as one of the key drivers of developments in 3D printing. Universities who are actively engaged in this have achieved considerable success by going beyond the limits of traditional research and teaching to direct commercial activities. For example, the University of Nottingham, has, in addition to its research activities in additive manufacturing, set up its own consultancy company, to enable it to engage more directly in the industry, and take better advantage of commercial opportunities[32]. With regard to the government helix, national governments such United States and China have gone beyond the traditional regulatory function to direct interventions to drive research and development, an activities to stimulate the market [33,34]. In the industry helix, stakeholders are prioritising research to achieve and maintain competitive advantage, in recognition of the knowledge intensive nature of additive manufacturing.

Developments in 3D printing also highlights the significant influence exerted by each of the helices on the others. For example, governments are driving significant changes in industry in terms of promoting adoption and sales of 3D printing equipment and products through public procurement. In the US, the promotion of 3D printing is being done through the establishment of America Makes, a public-private institute that was founded in 2012. The 3D printing industry has also, in line with stage three, seen the emergence of new trilateral networks and hybrid organisations bringing together actors from university, industry and government spheres (see Fig. 1). A good example is the joint 3D printing project in the United States, bringing together the University of Louisville, Concurrent Technologies Corporation, and the government owned National Institute of Standards and Technology (NIST). The project focused on development of better measurement techniques, a key issue that has limited the performance of 3D printing technology [33].

Finally, the development of 3D printing technologies is having a recursive effect within and outside the Triple Helix of university-industry-government spheres. The advent of 3D printing is having an especially significant influence on universities, in terms of how individual researchers, research groups and entire universities see their work. There is increased attention on intellectual property issues, and, as the Nottingham example show, universities are stepping out of their institutional boundaries to participate more directly in the market. It is also having some impact in society, including the emergence of prosumers who are accessing new opportunities to engage in home-based fabrication of items, or get involved as design co-creators of customised products. Governments are also increasingly interested not only in the economic and social values of 3D printing but also strategic security interests associated with the disrupted landscape of global manufacturing [35].

The dynamic interactions, role swapping and functional transformations described in the foregoing lead to the emergence of hybrid entities that are more able to produce high-valued knowledge at rapid pace, achieve and maintain competitive advantage in the market place, and create new “rules of the game” that are better responsive to, and supportive of, industry needs and aspirations. As the preceding discussions highlight and Table 1 shows, the seamless flow of information and knowledge exchange in a borderless Triple Helix enable actors is instrumental to the impact of the new hybrid trilateral entity.

3. Case illustrations

3.1. Methodological note

The following case illustrations are based on two countries: South

Table 1
Boundary-spanning functions across institutional spheres in additive manufacturing.

Functions	Institutional spheres		
	University	*Industry*	*Government*
Knowledge production and training	Research on new 3D hardware with improved speed and efficiency.	Collaborative partnership in R&D to achieve global competitiveness in additive manufacturing.	Launching national strategy and policy frameworks for research and development.
	Research focusing on new 3D software with improved design features and versatility.	Training and re-training workers in 3D techniques.	Grant funding for university and industry-led research projects in additive manufacturing.
	Research on new 3D materials, including wastes, to beat cost, achieve product differentiation and improve performance.	Supply universities with equipment and personnel for delivery of 3D curricula, including hands-on practical training.	Establishment and funding of national research institutes for additive manufacturing.
	Research on new and improved materials and methods for related and supporting industries in 3D printing.		
Market function	Establishment of 3D printing incubation hubs within university campuses.	Co-creation of a new supply chain in 3D printing.	Strategic public procurement drive to promote diffusion of 3D technology, products and services.
	Launching 3D spin off companies from university research projects.	Development and appropriation of new market opportunities in the 3D hardware sector.	Support and incentives for the participation of financial institutions in 3D printing.
	Setting up consultancy services in 3D printing.	Creation of new 3D platform opportunities in which end-users or intermediary organisations are co-opted as co-designers.	Government as venture capitalists in the 3D industry, complementing the role of financial institutions.
	Development of new 3D entrepreneurial ecosystems within university campuses.		Provision of support infrastructures, including power and broadband, to promote the growth of 3D printing market.
Regulation and control	Contribution to the development of technical and quality standards in 3D printing.	Establishment of pan-industry organisations to initiate and drive new policy interventions in support of the industry.	Establishment of regulatory frameworks for IP protection.
	Preparation of technical reports and policy documents.	Co-creation of new mechanisms to facilitate compliance with product liability and safety rules.	Establishment of appropriate supporting frameworks for 3D printing export oriented strategy.
		Development of appropriate ethics guidelines in the field of 3D bioprinting covering areas such as equal access and enhancement of human body parts.	Provision of tax breaks for 3D printing companies.

Africa and Kenya. In addition to representing two important regions in Africa (Southern Africa and Eastern Africa), they also represent two countries at different stages with regard to the development of additive manufacturing. These therefore provides a broader understanding of the challenges and opportunities for 3D printing across the continent. The cases draw from secondary data obtained through desk research. The sources of the data are: policy documents, technical reports, specialised conference proceedings, special features in newspapers, and journal articles. Across this spectrum of sources, the effort was made to triangulate and integrate the perspectives of 3D printing practitioners, policy makers, scholars, and other stakeholders in the industry and the wider community. The information obtained were coded into three key themes, in line with the conceptual premise of this paper, to explore the interactive and mutually reinforcing contributions of university, government and industry sectors.

3.2. *South Africa*

Additive manufacturing (AM) emerged in South Africa in the 1990s, at the time when the technology was known as rapid prototyping and there were only three systems in the country (D. J [36]. The following decades saw a steady growth of interest, driven by a recognition of additive manufacturing technologies as a key driver of competitiveness of the South African manufacturing sector. The advent of personal 3D printers (P3DP) contributed to the boom of the AM industry from the 2010s. The number of AM machines in South Africa grew from 90 in 2005 to 1500 in 2010. By November 2015, the number of AM machines had grown to 3,500, and 87% of them were entry level machines (D [37]. In 2016, the South African set out an additive manufacturing strategy that identifies four priority areas. These are: 1) Qualified AM technology for final part manufacturing for the medical and aerospace markets; 2) AM technology for impact in the traditional manufacturing sectors; 3) New AM material and technology development; and 4) SMME development and support programmes. The document highlights the critical importance of a multi-stakeholder approach drawing the triple helix of government, university and industry sectors:

> It is proposed that an AM Steering Committee consisting of representatives from key industry segments and associations, government and AM experts from R&D institutions, is established to primarily provide the strategic leadership with respect to the further refinement of the SA Additive Manufacturing Strategy and to oversee the implementation of programmes in support of the defined priority focus areas [37]; pp.vi).

The university sector. The South African university is playing a key role as a driver of the country's strategic agenda on additive manufacturing. A 2011 paper reported that 39% of the major universities were undertaking AM-related research, while 48% had in-house AM facilities [38]. Those numbers are expected to have significantly grown in subsequent years. In line with global best practices, the South African AM education strategy includes teaching and promoting AM technologies in the formal education sector, from primary to university levels; as well as provision of training programmes aimed at artisans, technologists, engineers and other professionals already engaged in the various industrial sectors. South African universities have been playing a leading role in this, through the development of research programmes to push the frontiers of knowledge in additive manufacturing, and the development of educational curricula suitable to the South African contexts [39]. Thus, knowledge production through research and knowledge dissemination through curriculum development and teaching go hand in hand. Some of the leading South African universities have also embraced the Third Mission of enterprise, along with research and teaching. For example, the Central University of Technology (CUT) established, in 1997, the Centre for Rapid Prototyping and Manufacturing (CRPM). The centre has emerged as one of the major players both in AM research and direct commercial activities. Their research and commercial activities focus on "three distinct areas, namely, medical applications, prototyping and rapid tooling with funding support from the DST, Technology Innovation Agency (TIA) and the NRF" [39]; pp.758). In other words, while the centre works in and with industry, it also continue to enjoy the support of the public/government sector through research grants. Like CUT, Vaal University of Technology (VUT) is contributing to the AM agenda through educational and training activities aimed at secondary schools in the area, and through the production and supply of Am components to local industry actors and entrepreneurs. As of 2017, VUT has more than 10 high-grade industrial AM machines, and it offers the highest resolution polymer laser sintering in South Africa. Like CUT, VUT enjoys strategic support and funding from the government, via the Technology Innovation Agency (TIA).

The government sector. The South African government's AM strategy is being led by the country's Ministry of Science and Technology. In a 2016 report, the minister for science and technology noted that "AM also holds much potential to improve competitiveness in traditional manufacturing sectors through shorter lead times, tool-less manufacturing, increased part complexity, freedom of design, incorporation of moving parts without assembly, customisation and diverse materials options" [37]; pp ii). Further, it states that,

> As a disruptive but also enabling technology, AM can support the South African government's objective to grow and diversify the economy via the nine-point plan announced by President Zuma in February 2015. Relevant aspects of this plan for AM are more effective implementation of a higher impact Industrial Policy Action Plan and unlocking the potential of small, medium and micro enterprises, co-operatives, townships and rural enterprises. The AM strategy will therefore support the implementation of national policy such as the National Development Plan and the New Growth Path [37]; pp.iii)

The South African government has played a lead role as convenor of stakeholders from the university and industry sectors to set and drive the agenda for AM in South Africa. It has done this through agencies such as the Council for Scientific and Industrial Research (CSIR) and Technology Innovation Agency, which provide grants and coordinate a range of public-private partnership activities in AM. For example, the government's R&D grant was crucial for the establishment of South Africa's first and leading home-grown AM platform, Aeroswift. Aeroswift was originally developed under the auspicies of the Titanium Centre of Competence (TiToC) and now hosted at the CSIR National Laser Centre. In addition to provision of grants, South Africa has also identified priority areas and strategic activities in which the government is expected to play the leading role. These include: 1)Ensure school-level interventions to facilitate exposure to the technology; 2) Provide widespread access to the technology at school level, e.g. through computer labs and CAD courses; 3) Establish a national AM curriculum for all design and engineering schools at Higher Educational Institutions; 4) Establish a dedicated bursary programme for pre- and post-graduate studies in the field of AM; 5) Secure National Research Foundation and Department of Science and Technology Research Chairs for AM; and 6) Establish national AM centres at strategic locations (D [37].

The industry sector. A major driver of the diffusion of AM technologies in the South African Manufacturing sector is the Rapid Product Development Association of South Africa (RAPDASA). Founded in 2000, RAPDASA is recognised as the official mouthpiece of additive manufacturing in South Africa. Among others, the organisation "connect leading innovators, entrepreneurs, industry partners and academics through various community engaging events"[40]. In another example amplifying the importance of industry-government synergy, RAPDASA works closely with the government's Department of Science and Technology, which funds many of its conferences, workshops, and community engagement activities. Its annual conference brings together hundreds of attendees and delegates from the academia, industry and public sectors. The activities of RAPDASA underline the need for an organised industry sector that can first create a critical mass of AM practitioners and innovators who can then play a key role in the diffusion of AM technologies in the South Africa's manufacturing sector. It also provides them with a viable platform to influence government policies, and also work closely with university researchers and research institutes to drive the agenda for new knowledge production in AM. This multi-stakeholder synergy is especially important because AM provides very good opportunities for the participation of small, medium and micro enterprises (SMMEs). Thus, South Africa has identified the following key areas of opportunities for SMMEs participation: 1)Production of prosthetics by use of AM technology; 2)Production of crowns and bridges for dental industry; 3)Production of customised hearing aids; 4) Manufacture of jewellery; 5) Use of AM in the creative arts industries (D [37]. Thus it is expected that a lot of university research activities, and government funding priorities, will be targeted at these priority opportunity areas. This will help create new jobs and contribute to South Africa's competitive advantage in those sub-sectors of the AM industry.

The preceding discussion reinforces the central idea that university, industry and government sectors need to work in collaborative synergy, rather than isolation, in order for a country to achieve optimum benefits and international competitiveness in additive manufacturing. As the South African example shows, each component of the triple helix play a leading role in their sector of prominence and expertise. However, they are also versatile and adaptable to play the role of the other in keeping with the boundary spanning model of the triple helix. For example, RAPDASA, an industry organisation organises an annual conference with the key aims of disseminating new knowledge. Similarly, Vaal University of Technology engage actively in commercial activity, manufacturing components which it sells to AM industry actors. Finally, the South African government runs a funded research institute, the CSIR National Laser Centre, dedicated to AM research and promotion.

3.3. Kenya

The university sector: In the production of 3D printing, universities in Kenya have played a key role. This position has led to university collaboration in fostering the country's additive manufacturing production. For example, the African Centre for Technology Studies and Kenyatta University have partnered to establish a 3D printing technology centre (Hall, 2016). The Centre aims to act as a 3D printing hub for capacity building, policy analysis and brokerage of information and technology. The main objective of the Centre is to encourage the next generation of African manufacturing workers by offering opportunities for 3D printing capability growth and exposure that crosses disciplinary boundaries. Three interlinked work streams are involved in the Centre: research, capability creation, and policy participation through information sharing and advocacy (Demissie, 2016). The collaboration also includes the development of research facilities, structures and processes to ensure long-term sustainability for the Centre (Demissie, 2016). As such, the Centre's main focus is on developing functional instruments and human resources to allow African countries to take advantage of the benefits of 3D printing technology and related fields of study. To leverage technology and related business and innovation ideas to stimulate sustainable growth, the Centre aims to educate and accelerate the policy-making process for 3D printing in Africa. They are also working towards achieving policy buy-in from African governments by creating a platform for policy debate (Demissie, 2016).

In addition, a number of leading universities are convening networking and knowledge exchange events bringing multiple stakeholders together to promote 3D printing. For example, Kenyatta University (KU) and the African Centre for Technology Studies (ACTS) co-organised an International Conference and Exhibition on '3D Printing for Sustainable Manufacturing in Africa' which was held in Nairobi, Kenya, May 26th-27th, 2016. The event was greatly supported by government and non-governmental organisations such as the National Commission for Science, Technology and Innovation (NACOSTI), United

Nations Industrial Development Organisation (UNIDO) and Kenya Industrial Research and Development Institute (KIRDI). It also features 3D printing firms, research institutes and manufacturers seeking to integrate 3D printing technology into their workflow (Kenyatta University, 2016). Thus, such collaborations in terms of creation of 3D printing centre and organising conferences aims to reach out directly to policy-makers and major players in different sectors of the economy, highlighting the configuration of emerging value chains to be generated by the adoption of 3D printing technologies.

The government sector: The government of Kenya has established institutions and mechanisms to create an enabling environment for ICT development that will greatly empower all key economic sectors (Government of Kenya, 2019). In this regard, the government has welcomed the advent of 3D printing as important to the development of ICT and manufacturing. More importantly, the government has shown its willingness to embrace and support 3D printing as both short-term and long-term solutions to public sector challenges. For example, the National ICT policy published in 2019 emphasised the role of government in driving the manufacturing ecosystem on 3D printing. As such, the government policy states that:

> "All innovation hubs and maker labs will be provided with a grant to acquire additive manufacturing capabilities. Physibles (data objects that are capable of being manufactured as a physical object using additive manufacturing processes) will be protected as intellectual property and the physical realisation of physibles will be similarly protected. This policy explicitly and specifically encourages the emergence of new enterprises around the creation of physibles" (National ICT policy, 2019; P. 20).

This kind of policy is an attempt by the Kenya government to encourage the development of technology ecosystems to support ventures and also allow entrepreneurs to develop skills, collaborate, and innovate around local challenges and solutions using 3D printing. For example, in 2009, the government partnered with the University of Nairobi to bring a global 3D printing laboratory to Kenya called "FabLab." (Ruvaga, 2014). FabLab is part of the international FabLab network which started at the Massachusetts Institute of Technology and serves as a small-scale workshop offering digital fabrication at the University of Nairobi. One of the aims of the establishment of FabLab is to support software and hardware Innovators in Kenya by creating a hub that provides collaborative community, Knowledge base and innovation business model Guidance with a core focus to increase Kenya's innovative competitiveness. The FabLab also serves as a model for the nation's leaders in policy, government, and industry, to experience, first hand, approach in promoting innovation and launching inventions while transforming traditional industries into digital fabrication agents (FabLab Kenya, 2020). Furthermore, the Kenya government has also attempted to increase the accessibility of 3D printing to the general public by encouraging secondary and tertiary schools to develop 3D printing capabilities. The National ICT Policy embedded this intent as a national priority and provided the impetus for the ministry to develop its sector policy on ICT in Education (Government of Kenya, 2019).

The industry sector: The industry in Kenya has also played a major role in the development of additive manufacturing. In particular, the major driver of additive manufacturing is an industry collaboration with universities. For example, the construction of Kenya's FabLab - an educational outreach of MIT that serves as a technological prototyping forum for learning and creativity by individuals – through the Science and Technology Park of the University of Nairobi has increased the diffusion of additive manufacturing in the country (Mashambanhaka, 2019). The FabLabs provides industry with industrial-grade resources, open-source software and a global community connection, as well as a range of other fabrication tools and technologies that help with the delivery of 3D printing technology (Fab Foundation, 2020). The creation of FabLab has been successful in increasing access to digital manufacturing technologies, such as 3D printing (Savonen, 2019). There are also local companies such as QTron Industries in Nairobi which has also benefited from collaboration with FabLab and now able to create and sell personal, easy to use locally-designed 3D printers. Similarly, Gearbox which is one of the largest makerspaces in Africa located in Nairobi, Kenya offers locals the use of digital manufacturing tools such as 3D printing to design, test and prototype their ideas (Gearbox, 2020). Furthermore, they hold trainings, provide technical support and offer mentoring and incubation space for new businesses (Gearbox, 2020).

Another example of industry collaboration with universities is the case of Kijenzi, a social enterprise start-up expanding 3D printing in Kenya (Kijenzi, 2019). Through Pennsylvania State University, co-founder Ben Savonen has led extensive research to improve the understanding of 3D printing on healthcare products in an environment in low resource settings. This is in line with other reported applications of 3D printing in healthcare contexts, including bio-printing and the cheap production of personal protective equipment (PPE) and medical equipment such as ventilators [41,42]. The latter assumed greater significance in the wake of Covid-19 pandemic. The Kijenzi study centred on understanding what low-resource communities need, what components can be effectively generated using 3D printing and the intersection between the two (Kats et al., 2019; Savonen, 2019). Consequently, Kijenzi now uses 3D printing to produce necessary medical supplies, and they also train Kenyans to use the technology. Kijenzi also developed a compact, low-cost, resilient 3D printing designed for use in humanitarian response in conjunction with Michigan Technological University (Savonen et al., 2018). This type of collaboration of industry with universities has helped to create opportunities for the development of start-ups in additive manufacturing.

Overall, it is clear that the development of additive manufacturing in Kenya has been driven by the triple helix of university, industry and government collaboration, with interlocking activities but also distinct contributions from each of the helices. For example, FabLab, a Nairobi-based co-working space for 3D printing entrepreneurs housed by the Science and Technology Park of the University of Nairobi attracts industry practitioners, offering them global community connections to gain practical experience and necessary resources to help with the creation and delivery of 3D printing technology products. The Kenya government heavily supported FabLab's ecosystem as part of its National ICT Plan (Ruvaga, 2014). FabLab also partners with the University of Nairobi and MIT, through which it gains access to relevant knowledge for the development of additive manufacturing. All these have helped foster the development of 3D printing in Kenya.

3.4. Towards an integrative triple helix model of technological leapfrogging in additive manufacturing

Extending our understanding how triple helix could be leveraged to promote leapfrogging, we develop an integerative model showing how the triple helix model of 3D printing could potentially interact with technological leapfrogging conditions to drive a 3D manufacturing revolution in Africa. As shown in Fig. 2, our integerative model shows how the various dimensions of triple helix in the context of 3D printing could drive this revolution.

Government and Condition 1. The first condition identified as necessary for technological leapfrogging in the large difference in wage costs between a leading nation and challenging nation. This is similar to the condition that accounts for relocation of sites of production from developed to developing countries. The cost of wages between developed and developing countries is significantly large. This is the case across sectors, but especially in manufacturing. For example, the average monthly salary in Nigeria, Africa's most populous country and largest economy, is $192.94. This contrasts with $3206.25 in the United States, that is, more than 16 times the average wage in Nigeria [43]. In effect, African countries, typified by Nigeria, have a lot of room to experiment with the new technology, at minimal labour cost. They are

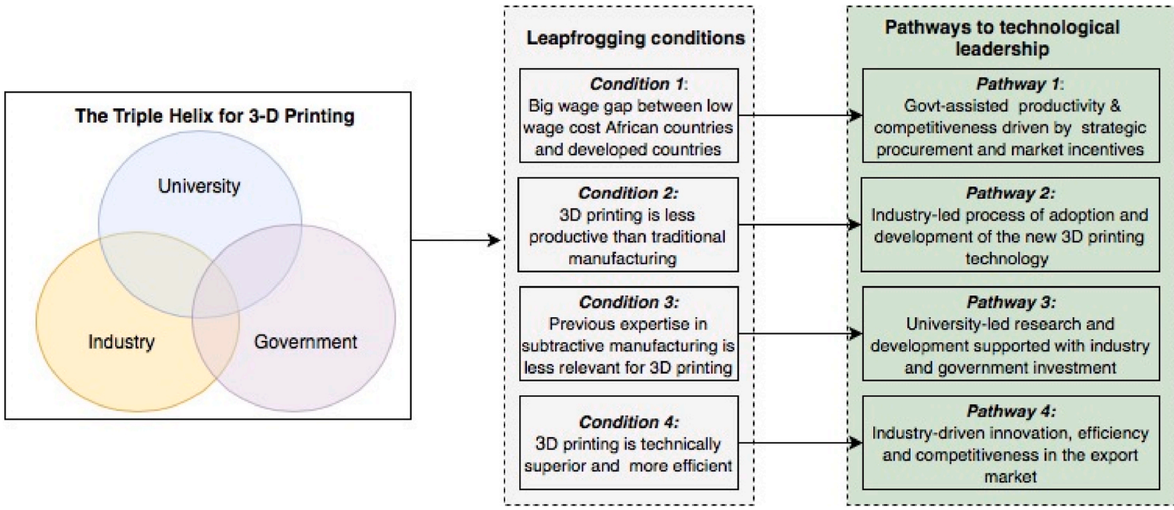

Fig. 2. A triple helix framework for technological leapfrogging in 3D printing.

also, compared to developed countries, better able to accommodate modest returns during the experimental stages, in terms of income and profits. While the economy of one associated with 3D printing presents a great possibility for developing countries, the market for 3D printing requires strategic policy incentives and market invigoration[44]. Thus, governments can play a key role at this experimental stage by, among others, using procurement to incentivise labour and drive productivity in 3D printing, ensure a stream of regular returns in income and profit, and drive activities in the export market. We therefore propose that:

P1: Government policies and strategic procurement interventions can provide incentives for high labour activity and productivity in 3D printing, and thereby increase the opportunity for Africa to gain technology leadership in additive manufacturing.

Industry and Condition 2: The second condition for leapfrogging is that the new technology should be deemed relatively unproductive compared to the old technology. While additive manufacturing is now seen my many as the manufacturing technology of the future, it has taken quite a while to catch on, considering the fact that the first 3D printer was invented about 40 years ago. Furthermore, questions remain as to whether or when the technology can compete with traditional manufacturing on an industrial scale, particularly in terms of mass production. Questions have been raised about the relative speed of the 3D printing process, in which it can take several hours to produce a single item. While this is a strong advantage with regard to customisation of products and production closer to the site of use/consumption, it also represents a limitation in terms of meeting mass demands for manufactured goods. Furthermore, at the moment, there are limitations in terms of materials available for use in the 3D printing industry-both with regards to variety and costs of materials [1]. All of these challenges in combination make 3D printing significantly less productive and less profitable than traditional manufacturing. As research and development progresses in 3D printing, these hurdles are likely to be overcome, and developing African countries are in a potentially stronger position to capitalise.

In order for this to happen, the industry needs to be actively mobilised and fully engaged in adopting 3D printing technology in order to precipitate a discontinuous leap of the new technology, thereby upending the trajectory of the old technology. While the old, subtractive manufacturing had established the dominant status within the global context, it is still presumed to be developing in the local African industrial context, thereby allowing better opportunities for the new 3D printing technology to gain traction. As more and more SMEs and other industry actors take up the technology, related industries and associated supply chains grow. All of these in combination generate the snowball effect that positive network externalities involving universities and governments as support acts in the development of 3D manufacturing sector. Thus, our second proposition states:

P2: *As more industry actors adopt 3D printing, supported by universities and governments investments in research, snowballing effects and new network externalities are generated to provide a pathway for African countries to gain technology leadership in additive manufacturing.*

University-industry synergy and Condition 3. With regard to the third condition for leapfrogging, which focuses on the relevance of knowledge and expertise of the old technology in the new technology, this is an area of unique advantage to a late starter country. As discussed in the previous sections of this paper, additive manufacturing represents a significant paradigmatic shift in the manufacturing landscape, not merely an incremental improvement in technique. This means that most of the knowledge and expertise accumulated over the centuries in subtractive manufacturing hold minimal relevance for the development of additive manufacturing. In effect, 3D printing is a perfect candidate for technological leapfrogging, as advanced countries have their head start practically wiped off. Furthermore, for reasons of technological lock-in discussed earlier, the attention and investment of advanced country, currently leading in 3D printing, continue to be at best divided. African countries can turn the screw by strategically focusing all attention and investment on developing the new technology and growing the market at home.

Universities can play a key role in this, in close partnership with industry actors. There is also a need for policy incentive from national governments. Given that 3D printing presents a lot of development opportunities, in form of challenges in key aspects such as 3D printing processes and materials, universities can develop new capabilities and allocate more human and material resources to tackle these challenges in direct response to industry needs. There are direct economic incentives for such university investments and specialisations [30], an important factor in a continent where the higher education sector is grappling with the challenges of limited funds. Furthermore, given that additive manufacturing is more knowledge intensive and less capital incentive, there are greater opportunities for university spin offs, and for the HE sector to participate directly as part of its third mission to contribute to economic growth. Thus, we propose:

P3: *When universities and industry focus attention and investment on developing 3D printing, there will be better opportunities for Africa to gain technology leadership in additive manufacturing.*

Industry and Condition 4. Finally, the fourth condition for leapfrogging is that the new technology must offer substantial improvement in performance relative to the old. While the new additive technology appears to be currently unproductive in the mass market, it represents technical superiority in several areas-in terms of simplified production process and the hyperflexibility of design and material requirements. Furthermore, as mentioned earlier, it efficiently replaces the economies of scale with the "economies of one". This "economy of one" will potentially revolutionise global supply chain configurations from raw material sourcing to production, quality control and inventory management. As more industry adopts 3D printing and the related industry and supply chains are transformed, the technical superiority of additive manufacturing technologies will precipitate increasing returns for industry actors and investors with time. In effect, the technical efficiency, hyperflexibility and efficiency of 3D printing will pay off in the mass market as consumers seek for better, cheaper and more accessible products.

P4: *The more industry actors harness the technical superiority and hyperflexibility of 3D printing to capture and create value, the better the opportunity for Africa to gain technology leadership in additive manufacturing.*

We bring these propositions together in a conceptual framework for technological leapfrogging in 3D printing (Fig. 2). The framework charts the links between leapfrogging conditions and pathways to technological leadership, driven by the triple helix of university-industry-government partnership. Thus, condition 1, focusing on low wage gap is linked with pathway 1 highlighting productivity and competitiveness associated with condition 1. Similarly, pathway 2 highlights how increased adoption of 3D printing can make the new technology more productive and profitable in the mass market. The same applies to the knowledge and expertise catch up (pathway 3), as 3D printing represents a discontinuous trajectory from the old, subtractive technology. Finally, pathway 4 highlights how the technical superiority of 3D printing can drive competitiveness in the export market.

4. Discussion

In this paper, we identified and addressed some gaps in the literature on 3D printing: (a) lack of conceptual framework to integrate the available literature on 3D printing; (b) lack of explicit links between the conditions for technological leapfrogging in 3D printing and role of the Triple Helix – universities, industry and governments – in driving 3D printing revolution in Africa; and (c) gaps in understanding the roles of African universities, industry actors and governments in the development of the technology and global expansion and growth of the market for 3D printing. We have shown how the triple helix of university, industry and government collaboration can drive explain and drive the opportunities for widespread adoption and potential leadership in 3D printing in Africa. In the following sections, we will highlight key areas in which African universities, industry actors and governments can contribute to the development of the technology and global expansion and growth of the market for 3D printing.

4.1. African universities and the future of 3D printing

The first area of contribution for African universities is developing a new generation of professionals and workers in 3D printing. This implies an overhaul of university curricula especially in, but not limited to, Engineering and Sciences. This revamping of engineering and science education will include new modules, as well as new programmes, in additive engineering. Aside from training new generations of 3D printing professionals, universities can also lead the charge in retraining existing manufacturing practitioners through the provision of short executive training courses. In order for these to be successful, academic staff will also need some retraining, and new laboratories and ancillary facilities need to be established. In the cases explored in this paper, it is evident that universities in South Africa are already playing a leading role in developing new curricula and research programmes in 3D printing. However, the development of new degree and postgraduate programmes are still in their infancy in South African universities. Instead, more attention appear to be given to provision of training and re-training programmes for engineers, technologists and other professionals already engaged in the manufacturing sector. In Kenya, universities are, compare to South Africa, in a relatively earlier stage of involvement and activities in 3D printing research and teaching. In both cases, which typify the highest levels of 3D printing promotion in sub-Saharan Africa, there is a long way to go if the countries are to realise the enormous opportunities for manufacturing revolution and potentials for technological leapfrogging. Of the two cases, South Africa has the most explicit and well developed strategy to identify specific sub-sectors to be targeted for 3D development in order to achieve global competitiveness.

There are two key pathways for African leadership in 3D materials research: first, given that most African countries are rich in natural resources, there are opportunities for original discoveries of new materials from experiments in new combinations and syntheses of various raw materials. Secondly, African countries have faced significant challenges with management of non-biodegradable wastes, including plastics and electronic wastes. There are also rooms for transdisciplinary research to create new opportunities for industry actors in product differentiation (Atiase, Kolade & Liedong, 2020). New research projects can investigate opportunities in areas of comparative advantage for Africa-based industries such as artefact prototyping. This is especially relevant in the context of the growing tourism industry in the continent and the associated growing demand for artefacts prototypes and souvenirs that recreate history and cultures associated with tourism destinations. Such research projects will likely involve a broad range of researchers from such immediate areas such as engineering and the sciences, but also disciplines such as history, anthropology, business, and other disciplines in social sciences, arts and humanities. Aside from teaching and research contributions, universities can host incubation labs in 3D printing where fresh graduates with business ideas can set up new ventures. Universities can also support and sponsor spin-offs from the new 3D research groups and institutes. These university business and technology incubation hubs can be effective intermediaries between the spheres of the university and industry, to support better linkages, increased commercialisation and higher uptake of university research[45].

4.2. New industry opportunities in 3D printing in africa

In both the Kenyan and South African cases, there is a clear recognition of the infrastructural deficit as a major barrier to 3D printing revolution in sub-Saharan Africa. Thus, the governments in both countries have prioritised infrastructural support and development as a key priority. This has yielded significant outcomes especially in South Africa, where the government has provided grants and support for procurement of industrial grade 3D printers in several university research centres, and in a national research institute. In turn, these supported centres are playing a key role as regional innovation organisers, as proposed in the triple helix, disseminating new knowledge and driving the diffusion of innovation in the South African industrial sector. Progress in infrastructural development is much more modest in Kenya, where 3D printing is mostly seen as a sub-set of a broader government agenda on digital transformation. Africa's long expected manufacturing boom has failed to take off mainly because the large infrastructural deficit, and the volatile political and regulatory environment, have in combination made African countries less attractive for foreign investments and location of production. In addition to these, African SMEs have been effectively taken out of the equation of global competitiveness on account of the huge capital set-up cost associated with traditional manufacturing. Thus, the liabilities of smallness and newness aggravate the struggle of African SMEs to survive the proverbial valley of death in the early years of operation. In these respects, additive manufacturing is an auspicious game changer that can potentially bring SMEs and micro-enterprises right back in the equation. The "economy of one" disrupts the global supply chain to the advantage of SMEs and micro-enterprises, especially resource-constrained enterprises in a continent like Africa. With low-cost 3D printers flooding the market, the cost of set up is significantly reduced for micro-enterprises to compete in the global market. Moreover, the cost of production is significantly reduced as 3D manufacturers produce on demand with practically no inventory. Furthermore, SMEs and micro-enterprises can harness the inherent advantage of proximity to end users in terms of direct contact with customers and the cheaper logistics of distribution. In order for these potentials to be realised, African countries need a well organised industrial sector-both in the downstream and up-stream sub-sectors. In the two cases considered, only South Africa has such a national organisation, known as the Rapid Product Development Association of South Africa (RAPDASA). RAPDASA has played a key role promoting 3D printing technologies, and liaising with university and government sectors to disseminate new knowledge, create jobs and advance the country's competitiveness in the manufacturing sector. In one example of a component of the triple helix playing the role of the other in a boundary spanning process, RADPASA is the convenor of a major international conference bringing together university researchers, industry practitioners and government officials. It is arguably the largest 3D printing conference in Africa.

The role of RAPDASA in South Africa highlights an important point: Working together with universities and government stakeholders, industry actors can incentivise suppliers of 3D printing materials. They can also spearhead the proliferation of 3D printing shops, thereby reducing, if not altogether removing, the need for large corporation in the mass production markets. The traditional large corporations can be replaced with big platform organisations providing licences for sophisticated designs and softwares to empower SME 3D printing shops. In turn, this can have a revolutionary impact on the employment landscape, not only with regard to new direct jobs created, but many more jobs created as a result of the boom in related and supporting industries along the transformed supply and value chains. For a continent currently grappling with youth and graduate unemployment, additive manufacturing can be a game changer by which the unemployment problem is turned into a great opportunity for a manufacturing revolution.

4.3. The role of government and implications for society

Both the South African and Kenyan governments have played significant roles in the drive for 3D printing in their countries. First, the governments has exercised its strong convening powers to bring universities and industry actors together. In South Africa, governments is using procurement to stimulate the market and thereby drive the adoption and diffusion of 3D printing hardware, software and products. This is very important for the development and expansion of the domestic market for 3D printing. They have also, again in the South African case, provided some leadership through the establishment of national standard agencies, and national bodies overseeing research grants and capacity building in additive engineering. Going forward, governments can play direct roles in accreditation and promotion of new undergraduate and postgraduate programmes in additive manufacturing. Furthermore, given that inadequate infrastructure and institutional voids are two major obstacles to industrialisation in Africa, African governments have a new opportunity and new incentive to undertake focused and strategic investment with clear, measurable returns in mind. These returns can be in terms of enhanced national productivity, increased GDP, new employment opportunities, market expansion and inclusive growth.

In addition to the dynamic synergies and interactions among the three primary institutional spheres, this study also raises an important question for the African society: How does our argument about the triple helix model to technological leapfrogging in additive manufacturing square with the realities of unemployment and stagnant economic growth? For most African countries, the agricultural sector continues to be the largest employer of labour (AGRA, 2018). While the services sector, especially mobile telecommunications, has experienced significant growth over the past decade, there continues to be a big deficit in the labour market in terms of employment opportunities. This is partly due to the fact that the services sector has limited absorptive capacity for profitable employment. To address the problem of unemployment and achieve economic growth, it is often argued that attention must be paid to the manufacturing sector as it tends to have relatively high capacity to absorb labour. In line with this, our paper focuses on the triple helix model of university-industry-government partnership can contribute to national wealth creation and economic growth [25]. Our discussion about the prospects for triple helix model to drive 3D printing revolution in Africa aligns with the drive a structural transformation of Africa's economy from its agrarian base to one where manufacturing and services take higher shares. In line with this, the triple helix model of technological leapfrogging in additive manufacturing can facilitate Africa's leading role in the unfolding fourth industrial revolution [5].

Finally, the protracted disruption of global supply chains precipitated by successive strains of Covid-19 pandemic presents a unique opportunity for governments and stakeholders to accelerate 3D printing revolution on the African continent. At the time of writing, the latest variant of Covid-19, Omicron, has disproportionately affected African countries with shutdown of borders and ports. Governments can enact supportive policies and provide incentives for African manufacturers to adopt 3D printing which requires much smaller inventory and limited need for warehousing.

4.4. Limitations

This study has some limitations in terms of the methodological approach, its aims and objectives, and the empirical strategy. These limitations, in turn, present new opportunities and agenda for future research. Firstly, the paper is mainly a conceptual paper with complementary case illustrations to reinforce the conceptual propositions. As such, it draws mainly from critical synthesis of the extant literature on technological leapfrogging and the triple helix, applied to the context of 3D printing in Africa. The case illustrations then aggregate and triangulate secondary data from policy documents, technical reports and selected journal articles to discuss the contributions of the university, industry and government sectors to the development of 3D printing in two African countries with contrasting developmental and regional profiles. There is therefore a scope here for future research to explore primary data, both qualitative and quantitative, to deepen understanding of opportunities and challenges in the African 3D printing landscape, and also for cross-country comparisons. Secondly, the paper offers a panoramic view of the 3D printing landscape. This is pertinent within the scope of this present paper, but leaves significant gaps in knowledge about sub-sectoral peculiarities and opportunities. For example, South Africa has identified specific opportunities for 3D printing in the health sub-sector (production of prosthetics, customised hearing aids, etc) and creative and arts sub-sector, among others. Future studies can aim to disaggregate firm level data according to sub-sectors and across countries, using cross-sectional surveys and longitudinal data. Thirdly and finally, this paper did not make detailed distinctions between the upstream and downstream sectors in 3D printing in Africa, how the affect one another, and how developments in both the upstream and downstream sectors are influenced by the contributions of university, industry and government sectors. This is a fruitful areas of future research that presents opportunities for cross-country knowledge exchange and diffusion of industry best practices across the African continent.

5. Conclusion and recommendations

This paper has taken a conceptual approach, with case illustrations, to discuss the potential and opportunities for additive manufacturing revolution in Africa, drawing ideas from the Triple Helix model of university-industry-government collaboration and the theory of technological leapfrogging. It is argued that, with the advent of the disruptive 3D technology in the manufacturing sector, African countries can no longer rely on the advantage of factor conditions, even with wage increase in China suggesting Africa should be the new preferred destination for international location of traditional manufacturing production. Instead a new opportunity has emerged as a result of the disruptive impact of 3D technologies on the global supply chain, bringing microenterprises back into competition. With this a new race has also emerged, and African countries have a great opportunity to catch and leapfrog the leading nations in 3D manufacturing. This opportunity is underpinned by the favourable positioning of African countries in relation to the conditions for leapfrogging. First, the large wage increase between African countries and the advanced industrialised countries is best suited for leapfrogging. African countries have more room to accommodate relatively lower wages and modest profit in the early stages of 3D technology development and adoption. Furthermore, given that the technology is much cheaper to set up and run for on demand production, it is best suited to the otherwise disadvantageous industrial architecture of African countries, where micro, small and medium scale enterprises (MSMEs) dominate the market and are previously unable to compete with big corporations domestically and internationally. 3D printing brings these MSMEs back into play in the new landscape of additive manufacturing. In addition, the significant scepticism among developed nations over the future profitability of 3D printing for mass production offers African countries an auspicious to drive ambitious projects in research and development of improved processes and new materials for additive manufacturing and related and supporting industries.

From the benign to the transformative, our paper makes three important contributions. First and foremost, we draw on the triple helix model and technological leapfrogging theories to propose a new, integrated conceptual framework that explains how synergy and collaboration between university, industry and government actors can drive the development and widespread diffusion of 3D printing technologies in Africa. Secondly, the paper highlights the disruptive impact of 3D printing technologies of global manufacturing supply chains, and how this provides a unique opportunity for African SMEs and microenterprises to drive industrial revolution in Africa and potentially compete on the global scale. Thirdly, the paper contributes to the technological leapfrogging literature to unpack potential conditions that can drive the revolution of additive manufacturing in Africa.

Our study also has some practical implications for the management of triple helix actors - universities, industry and government. To drive the triple helix model of technological leapfrogging in 3D printing, universities, industry and government in Africa must be prepared to play active role in enabling the necessary conditions. This can be achieved through a transformative reset of the university-industry-government relationship. Africa's new entrepreneurial universities need to embrace the third role of economic development in order to be more effective in the traditional roles of research and teaching. This will entail the introduction of new modules and programmes in additive manufacturing across universities, the emergence of new transdisciplinary research groups leading ambitious projects, and the establishment of incubation units and support for spin-offs. In turn, the industry need to emerge from self-imposed isolation to embrace enormous opportunities for new ideas and research and development services that active partnership with universities bring, thereby raising their competitiveness in the knowledge economy. Finally, governments need to shed the toga of passive clientele to engaged partners contributing actively to knowledge production and market activities, in addition to the traditional role of regulation. The new hybrid organisations emerging from this Triple Helix of university, industry and government interaction can drive the fourth industrial revolution on the continent-including, but not limited to, 3D printing. Future research can explore this in more detail. There are opportunities for original, interdisciplinary research into how rapid prototyping can bring the extensive riches of African culture and history to life in the global market, including tourism. This will align well with the strategy for product differentiation. There are also opportunities to investigate the development of new 3D printing materials using the extensive natural resources, as well as the huge waste problem, as starting points. Finally, given the growth of ICT and mobile telecommunications in the continent, there are opportunities for fruitful research into new digital techniques, methods and softwares for 3D printing.

In conclusion, we have taken a step to extending conceptual understanding of the emergence of triple helix model of technological leapfrogging in 3D printing in Africa. The propositions we develop in the paper, based on a well-established triple helix model and technological leapfrogging, can provide a strong basis for empirical research on 3D printing in Africa. It also has significant implications for triple helix actors - universities, industry and government in driving the fourth industrial revolution of 3D printing in Africa. We hope that this work will encourage other scholars to pursue a more systematic and theory-driven exploration of the triple helix model of technological leapfrogging in additive manufacturing in Africa.

Author statement

The authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the editorial process. He is responsible for communicating with the other author about progress, submissions of revisions and final approval of proofs.

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