INNOVATION ENVIRONMENT'S ROLE IN SUPPORTING INDUSTRY 4.0 TECHNOLOGY ADOPTION TO ADDRESS EFFECTS OF COVID-19

Health systems were severely strained at the start of the COVID-19 pandemic, where the demand for Personal Protection Equipment (PPE) could not be met. The challenge faced by many countries was how to innovate quickly to create PPE and other needed solutions. The subsequent research gap identified was a lack of practical insights on how to support such novel technology adoption, particularly those that stem from Industry 4.0 (I4.0) within a developing world context. To address this previous literature on I4.0 technology, the role of innovation environments and theoretical principles of technology adoption was reviewed. A practical case from an academic makerspace based in a South African university was then assessed. It was selected due to its direct role in rapid solutions development of PPE using additive manufacturing (AM) until such a time that manufacturers could set up production on a larger scale. It was found that AM and other novel technologies have facilitated innovative solutions to address the significant impacts of the pandemic. Key to which were practices identified of an innovation environment that supported early-stage adoption of AM to achieve this even in a developing country context. The findings imply that innovation environments offer an agile platform to leverage innovation by streamlining certain critical success factors of I4.0 technology adoption, which is presented in a model. However, individual skills developed by such environments to enhance innovation capabilities within this paradigm require further research.

Keywords: 3D printing; Additive manufacturing; COVID-19; Fourth Industrial Revolution; Innovation environment; Makerspace; Rapid prototyping

1. Introduction

The pandemic attributable to SARS-CoV-2 (COVID-19) shocked existing paradigms on a global scale, where several countries were left scrambling to manage numerous adverse effects, including the loss of human life [Armijo *et al.* (2020)]. South Africa (SA), a developing world country, was no exception [World Health Organisation (2021)]. In an attempt to mitigate impending impacts, the country went into lockdown on March 26th, 2020, after the first cases were identified. This was to facilitate disaster planning and prepare for the anticipated wave of infections [NICD (2020)]. In addition, hospitals were pivotal centres to test and treat patients with COVID-19, causing healthcare workers to be exposed to the virus at much higher levels than the average person [Belhouideg (2020)]. Therefore, it was deemed vital that they were provided with Personal Protection Equipment (PPE) and other resources to prevent further transmission and continue delivery of their vital services [Armani *et al.* (2020); Singh *et al.* (2020)].

However, with the pandemic situation, supply chains were under severe strain [Tino *et al.* (2020)] despite advances in technologies [Ferrás-Hernández *et al.* (2019)]. This was because supplier capacities could not meet demands quickly enough [Mueller *et al.* (2020)]. This, alongside other cascading effects, caused concerns across the globe regarding the provision of needed medical equipment and PPE [Manero *et al.* (2020)]. Hence, a call for innovation went out to address this. A technology which has been strongly associated with Industry 4.0 (I4.0) came to light, additive manufacturing (AM) or three-dimensional (3D) printing [Lee *et al.* (2018)]. Existing literature has noted various forms of AM within a global context [Singh *et al.* (2020)], its applications [Lu, (2017)] but also how it integrates with other I4.0 technologies [Xu *et al.* (2018)]. Reasons for its adoption include rapid prototyping of solutions for production or testing activities, to advance methods for superior industrialisation [Prince (2017); Wesemann *et al.* (2020)].

Within the context of the pandemic, the adoption of AM was shown to facilitate rapid innovation by addressing supply chain shortages of PPE. This was achieved by producing face masks, straps, valves, ear savers and other items until mass production systems could meet demand [Choong *et al*. (2020); Singh *et al*. (2020)]. The rapid production of these items was supported by a group of stakeholders including research and development (R&D) divisions of companies, universities, makerspaces, laboratories and private hobbyists [Mueller *et al*. (2020)]. Notwithstanding, these stakeholders form part of larger innovation ecosystems, which have been shown to act as value creation mechanisms between actors in both academia and industry [Asplund *et al*. (2021)]. In more developed regions such as Europe, specific mechanisms such as Digital Innovation Hubs (DIHs) [European Commission (2018)] have been implemented, where, even prior to COVID-19, have acted as catalysts to stimulate innovation through the adoption of digital technologies [Macedo *et al*. (2021)]. This is achieved by offering key functions such as testing viability, identifying investors and developing needed skills, to name a few [Sassanelli *et al.* (2021)]. Moreover, they support Small and Medium-sized Enterprises (SMEs), as they are critical in economic development, to leverage digital innovation by offering platforms to foster networks and build key partnerships [European Commission (2020)]. As a result, the region continues to lead in the I4.0 context [Crupi *et al*. (2020)].

These mechanisms offer symbiotic collaboration and functions that enable novel technology adoption [Lu (2017)]. However, despite the several advancements, research has primarily focused on developed regions that have strong capabilities in driving automation with emerging technologies, as well as benchmarks in terms of support structures such as DIHs. As such, a gap in literature was identified, not concerning the importance of such technologies, rather insights into supporting the adoption of such novel technology to increase innovation performance and knowledge capabilities towards sustainable competitive advantage [Moeuf *et al*. (2020)] within developing countries A question raised in this regard is: "*How can innovation environments in developing countries enable novel technology adoption to develop relevant solutions?".*

To answer this question, two approaches are used from a methodological perspective. Firstly, previous literature on the pandemic in which technology adoption facilitated innovation is reviewed. This includes constructs of technology adoption models and critical success factors (CSF) needed for I4.0. For this study, the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) [Verma and Prakash (2021)] are primarily used due to their usage within I4.0 literature [Rüßmann, (2015)], and by extension, the Fourth Industrial Revolution (4IR) [Chang (2017); Gangwar *et al*. (2015); Luthra *et al*. (2020); Rahman *et al*. (2017)].

Secondly, a case study from an academic makerspace based within a South African university is presented. This was selected as the country is channelling efforts to innovate through the use of novel technologies, including AM [Ayentimi and Burgess (2019)], where academic institutions are noted as pivotal stakeholders in facilitating adoption [Chang (2017)]. The environment was also a direct stakeholder in developing rapid solutions of PPE using AM until such a time that manufacturers could set up production on a larger scale.

The objective of this study is to provide insights by developing a model on how to enable novel technology adoption of I4.0 such as AM [Xu, Xu and Li (2018)] using innovation environments [Sharma (2021)]. According to Hajoary (2021), Moeuf *et al.* (2020), Pozzi *et al*. (2021) and Sony and Naik (2020), several CSF need to be considered.

This study adds to this and existing technology management literature on innovation environment's ability to streamline novel technology adoption that stem from I4.0, which was accelerated by the pandemic, even in a developing world context.

This document is organised into three broad themes to address the research question. The first section reviews previous literature on the pandemic, innovating with technology, enhancing innovation with technology, forms of existing innovation infrastructure and theoretical perspectives on technology adoption. The second section reviews the methodology and notes why a case is used to determine if innovation environments can be one of several societal movements to address real-world problems. Findings are then reviewed, noting the issues of innovating with novel technologies such as AM and the limitations identified. Finally, concluding remarks and reflections on future initiatives on the role technology plays and how they can be further integrated through innovation environments is presented.

2. Background

The severe acute respiratory syndrome, referred to as COVID-19, has been extensively analysed in recent months due to its impact and consequential pandemic [Armijo *et al.* (2020); Tino *et al.* (2020); Verma and Prakash (2021)]. Research shows that this novel virus can sustain itself for up to 3 hours in the air and 72 hours on various materials, including plastics and metals [World Health Organization (2021)]. This, alongside high viral loads in the upper respiratory tract with asymptomatic transmission modes, facilitated the virus's ability to rapidly spread across the globe [Wesemann *et al*. (2020)]. Sample rates for the world obtained from the World Health Organisation [2021] shows that, as of April 11th 2021, there were severe impacts on human life. 135 057 587 confirmed cases globally and 2 919 932 deaths as shown in Fig. 1. As of April 11th, 2021, SA had 1 557 527 confirmed cases with 53 256 deaths.

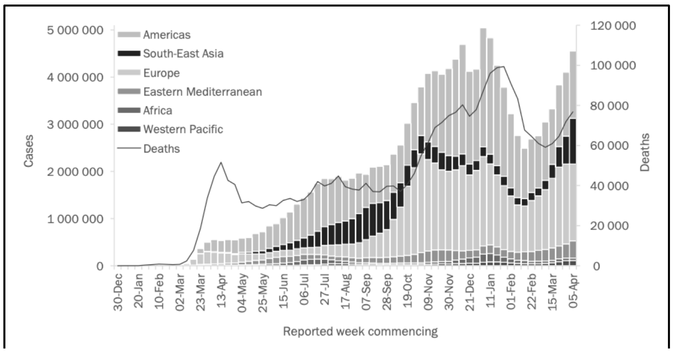

Fig. 1. Confirmed COVID-19 cases and deaths globally as of April 11th 2021 [World Health Organisation, (2021)].

In an attempt to mitigate exposure, social distancing and PPE usage were claimed to prevent the viruses spread and reduce deaths as far as possible [Koven (2020)]. A study conducted by Lindsley *et al.* [2014] tested the effectiveness of PPE through several experiments. Based on parameters, the findings suggest that a face shield reduces COVID-

19, which carries similar airborne properties such as influenza by approximately 96 percent, supporting that such PPE is vital to protect frontline workers.

2.1. *Innovating with technology*

Even during a pandemic, literature shows that innovation was able to ensure a large scale adoption of technology across economies to address challenges through the global community movement [Brem *et al.* (2021)] which leveraged rapid advances in I4.0 technology towards the next generation of manufacturing [Younes *et al.* (2020)]. Innovation then was not stagnant in this context [Corsini *et al.* (2021)] as various drives to rapidly prototype solutions were occurring across the globe [Coronado-Medina, Arias-Perez and Perdomo-Charry (2020)]. This was facilitated by adopting I4.0 technologies that forms part of the 4IR, which, as a premise, is the integration between the physical, digital and biological spheres of human existence with technology [Schwab (2017)].

A key technology within this paradigm that supports rapid prototyping is AM [Rüßmann, (2015)]. Steenhuis *et al*. (2020) stated that this technology is novel as it has various applications but remains complex in terms of its usages and application. However, despite the complexities, it has several advantages from an innovation perspective when adopted, including testing of concepts, costing benefits, and being distributed across various geographical areas quickly [Matos and Jacinto, (2019)].

Several examples were identified that support this. In Italy, a hospital ran out of valves required for respirators vital for COVID-19 patients who needed help breathing. The leading supplier could not meet the increased demand, so an engineering firm in Brescia used AM to address the high demand for respiratory valves and created printable versions quickly [Tarfaoui *et al.* (2020)]. Whilst this was occurring, mass production of these valves could be developed. In the United States of America (USA), a Boston based company developed testing swabs for COVID-19 and could print up to 75 000 swabs per day. This mass production allowed hospitals to access large quantities for testing noted as essential [World Health Organisation (2021)]. A Saudi Arabian team were printing wrist clasps for surgeons to hold a bottle of sanitiser, which acted as a constant reminder to sanitise. These are only some of the examples occurring across the globe using AM [Wesemann *et al.* (2020)]. Hobbyists and the maker community also aided in developing PPE utilising many devices with open-source design files. Within the community, the focus was the users level of protection, including the ability to wear an N95 mask underneath the face shield [Seo-Zindy and Heeks (2014)].

2.2. *Enhancing innovation through technology and infrastructure*

From a strategic perspective, innovation, has been a vital construct to remain relevant [Verma and Prakash (2021)], where businesses have channelled resources and efforts into R&D to maximise economic value [Asplund *et al.* (2021)]. This sentiment remained true even during times of crisis, as was experienced at the start of the pandemic [George *et al.* (2020)].

However, several variables, including infrastructure, collaborative mechanisms, individual competencies and collaboration between task forces impacts organisations effectiveness to innovate [Walsh, Przychodzen and Przychodzen (2017)]. These variables place a vast amount of pressure on actors such as academia and business to be agile in adopting relevant technologies [Hooton (2018)], which depends on their knowledge base [Guinan, Parise and Langowitz (2019)]. In several instances, academic institutions who perform R&D can be considered vital in this scope to drive inter-disciplinary research, where facets of knowledge can be created and combined to address pertinent issues [Antonites and Van Vuuren (2014); Van Der Schaaf and Daim (2020)]. Developed regions have used DIHs to not only share knowledge [Crupi *et al.* (2020)], but also generate it for SMEs by channelling digital technologies with initiatives such as the Digital Innovation HUBs and Collaborative Platform for Cyber-Physical Systems (HUBCAP) [Asplund *et al.* (2021); Moeuf *et al.* (2020)]. Within these hubs, technology, including those of I4.0, have been shown to create value, even in times of crisis [Wegmann and Schärrer (2020)]. By increasing the adoption of such technologies to drive innovation and address needs quickly, the purpose of an innovation environment to light [Masood and Sonntag (2020)], as it can facilitate the rapid response to challenges and opportunities [Kruger and Steyn (2020)]. If done well, these environments can enhance the innovation capacity [Das (2020)] that is required by an organisational strategy to address ever-changing needs and expectations [Coronado-Medina *et al.* (2020); Seo-Zindy and Heeks (2014)].

Part of this infrastructure includes innovation environments such as a makerspace. For this study, a makerspace is referred to as an environment that focuses on creating and prototyping through a Do-it-Yourself (DIY) philosophy [Sharma, (2021)]. In some cases, reverse-engineer commercial objects and redesigning them for a specific need [Seo-Zindy and Heeks (2014)]. They have been embedded in various scopes, including schools, universities, libraries and museums [Adams *et al.* (2018)]. Research also notes that these spaces are supporters of innovative activities across science, technology and art [Armani *et al.* (2020)]. Their role has been seen to enhance research through the exchange of ideas and collaboration, supporting entrepreneurial development and even design enhancement towards technology transfer. Technology transfer can be described as the process of transferring and disseminating technology from its creator to someone else, including corporate entities, to realise value from innovation activities [Kruger and Steyn (2019)]. As a result, makerspaces have received scholarly interest and stand to evolve critical aspects of technology adoption, including those of I4.0, through intellectual structures towards knowledge creation and innovation [Martin and Thiel (2021)]. This includes the support of business spin-offs [Steenhuis *et al.* (2020)]. Importantly though, to effectively implement such infrastructure, institutions readiness to leverage such advanced technology needs to be assessed. Fortunately, theoretical maturity models alongside CSF exist within the I4.0 construct to establish this [Sassanelli *et al.* (2021)].

2.3. *Theoretical perspectives to ensure effective technology adoption*

I4.0 technology adoption is vital for stakeholders to improve their “triple-bottom line” through sustainable competitive supremacy [de Sousa Jabbour *et al.* (2018)]. However, it requires certain CSF to be realised [Sony & Naik (2020)]. By considering established CSF and contextual factors per Pozzi *et al.* (2021), strategies and associated activities which have been noted as vital [Verma and Prakash (2021)] can be identified to support effective implementation of I4.0 technologies [Santos (2017)].

From a theoretical perspective, by leveraging symbiotic collaboration between teams and resources within a specific project, an innovation environment can directly address several CSF towards the effective adoption of I4.0 technology [de Sousa Jabbour *et al.* (2018); Pozzi *et al.* (2021)]. Notwithstanding, this study considers how the innovation environment under investigation channelled activities to leverage rapid advances in industrialisation using AM to address the challenges of the pandemic [Steenhuis *et al.* (2020)]. A key aspect was how this technology was adopted to support innovation to ensure a large-scale diffusion across geographical economies [Seo-Zindy & Heeks (2014)]. This supports earlier findings where European regions have already realised the role innovation environments have in addressing CSF using I4.0 technologies [Schumacher *et al.* (2016)].

With regards to technology adoption, various arguments surround the models and theories in place that address the phenomenon. Tornatzky and Fleischer (1990) proposed the Technology, Organisation and Environment (TOE) framework for technology adoption while Davis, (1985), who proposed the TAM model [Gangwar *et al.* (2015)] saw significant uptake as it was easy to understand and includes perceived usefulness (PU) and perceived ease of use of technology (PEoU).

A more comprehensive model was later proposed by Venkatesh *et al.* (2003) called the UTAUT model. The UTAUT model proposes a critical aspect of information systems and technology management research to explain technology's acceptance and subsequent usage. This model is based on eight other models and theories. The purpose is to define CSF to predict behavioural intention to use and adopt the technology. The four primary constructs of UTAUT consists of (1) Performance expectancy, the provided benefits to the user. (2) Effort expectancy, referring to the technologies ease of use. (3) Social influence, noting how other users influence the users' perceived usefulness and (4) Facilitating conditions that considers the support and integration into existing systems.

For this study, we consider constructs of the TAM and UTAUT models as seen in Fig. 2. The primary purpose is to align from a theoretical standpoint on the CSF that have been used and confirmed to affect I4.0 technology adoption [Venkatesh *et al.* (2012)]. For example, teamwork and collaboration, as it has been linked to organisational performance to develop trust and effectively integrate I4.0 technologies across business units demonstrating usefulness and positively impacting their ease of use [de Sousa Jabbour *et al.* (2018)]. Subject areas of I4.0 that these models have been applied to include autonomous cars [Rahman *et al.* (2017)], cloud computing [Gangwar *et al.* (2015)], smart home technologies such as IoT (Nikou (2019); Shin *et al.* (2018)] and supply chain management with IoT [Luthra *et al.* (2020)]. A vital construct stemming from the UTAUT model, facilitating conditions, demonstrates a gap for further research. These conditions look to the organisational strategy and technical infrastructure as CSF, noting how this will impact the overall system during technology adoption [de Sousa Jabbour *et al.* (2018)]. This aligns with the study’s objective that seeks to identify innovation environments role as infrastructure in streamlining adoption.

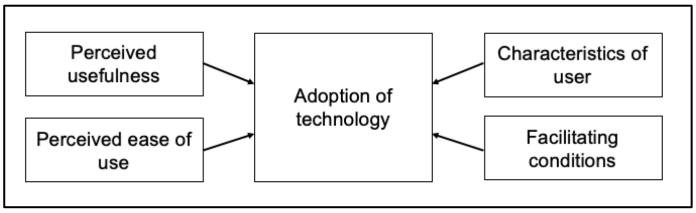

Fig. 2. Technology adoption based on TAM Model and UTAUT Mode within I4.0 [Davis (1985); Luthra *et al.* (2020); Nikou (2019); Venkatesh *et al.* (2003)].

2.4. *Summary*

The COVID-19 pandemic caused several evident impacts on human society, where effective solutions were required immediately. The tools to do so have improved due to novel technologies of the I4.0, such as AM, and improved innovation ecosystems. It is argued that technology is a CSF of strategy and innovation, where responses now and into the future could be improved if well implemented [Sony and Naik (2020)]. The focus was on the adoption of such technologies to innovate in various spheres of I4.0, with the TAM and UTUAT models identified as relevant in this regard alongside certain CSF. The purpose of this study is to look at how to enable technology adoption such as AM through innovation environments [Steenhuis *et al.* (2020)]. The emphasis of this research is to help in understanding the role innovation environments have towards enhancing technology adoption to address real and pertinent issues.

3. Methodology

Previous literature reviewed demonstrated how AM as a disruptive technology was used to facilitate innovative solutions to address the impacts of the pandemic across the globe. Theoretical fundamentals of technology adoption were also reviewed, noting usages of technologies associated with I4.0 that forms part of the 4IR. The second method used for this study is the assessment of a practical case relating to the rapid adoption of smart technologies, mainly AM, at the start of the pandemic.

A case study was selected because the research called for an in-depth review of a specific phenomenon. The phenomenon itself was investigating how to streamline novel technology adoption. This pertained to an organisation within the developing world of SA. As such, a case study was deemed appropriate, as this research called for an in-depth investigation into activities, methods and practices used by an innovation environment to quickly address problems through effective adoption of I4.0 technologies [Dalmarco *et al.* (2019)]. The reason for only one case assessment was that the researchers were directly part of the development of the solutions within the environment during the time of adoption, allowing in-depth analysis of how it was streamlined on a practical level. Moreover, the environment offered insights into strategic collaboration activities as other innovation environments were sourced to deliver the solutions. With these insights, the case can be argued to have provided time-relevant insights into the activities of the study [Yin (2017)].

To achieve this, the academic makerspaces activities that enabled rapid response and possible reasons for its innovation capabilities were directly observed. The coding used to log this was reports, documented achievements, news items, processes from observations, field notes and publications. This state of coding was used until categories emerged to present findings that could be used to create the model. As per Fram (2013), inductive coding was used based on the constant comparative method to identify patterns and organise it into logical sections. This constant comparison allowed the researchers to reach a point where theoretical saturation for this case was obtained, and no additional coding within the studies parameters were noted. In other words, the categories were developed with properties and dimensions identified during the start of the pandemic. Using this method, essential practices that supported PU and PEoU could be identified. Moreover, how an innovation environment can enhance facilitating conditions towards improved adoption, if at all could be determined. This was a cross-sectional study due to the rapid nature of the response. Fig. 3 presents an overview of the methodology.

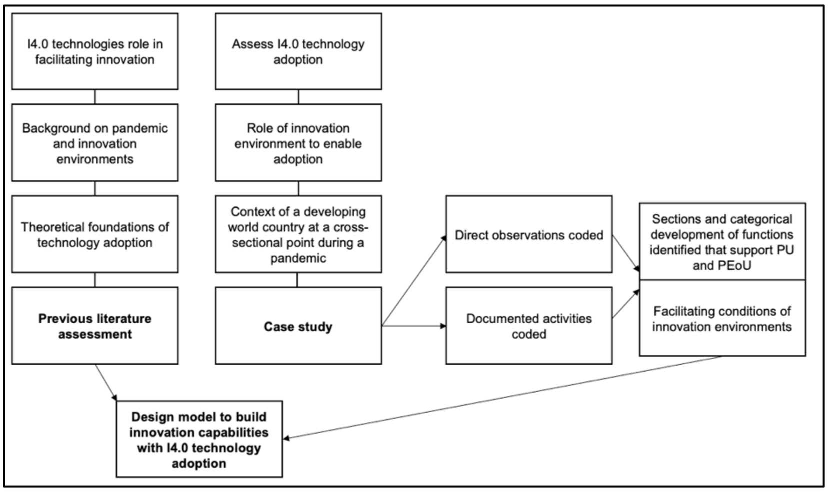

Fig. 3. Research methodology overview.

4. Findings from the case study

4.1. *Academic makerspace as an innovation environment*

The Makerspace Centre under investigation was founded in April 2015. It is one of the first academic makerspaces in Southern Africa. Since then, it has developed a series of past successes to demonstrate how innovation can be integrated into the academic and business community. This ranges from the enhancement of research outputs across disciplines to develop new teaching and learning methods. One of which is the introduction and adoption of novel technologies brought on by the 4IR. From a business perspective, the usage of the space has seen training towards skills development to improve ideation and design thinking. These practices aim to ensure the usage and integration of technologies towards new business development and technology transfer. Through the effective diffusion of technology, there appears to be a drive to realise the full potential of technology and the associated potential it unlocks, from improved productivity to societal transformations. The current crisis showed significant pressures placed on ICT by emphasising working remotely and communicating through different mediums. This is said to continually impact efficient tools for long-distance communications and professions that impact society, such as information systems, where consumers are becoming sources of innovation as well [Rayna *et al.* (2015); Peffers, Tuunanen and Niehaves (2018)]. One of which is rapid prototyping using the Internet of Things (IoT) development and 3D printing for rapid prototyping [Chong *et al.* (2018)]. This was done in the space. For example, over several months, with a doctor specialising in health physiology, the team developed best methods and practices using AM to enhance the learning experience of a visually impaired student. This was achieved by engaging with the user to identify needs guidance and then, through collaboration, develop iterations until a viable solution could be created [Punchoo, Kruger & Wolvaardt (2018)]. In other instances, within the veterinary sciences, lion teeth prototypes using plastics were developed to enhance procedures towards teaching and learning by providing access to resources not readily available. There also continues to be the development of testing equipment in the bovine and malaria fields [Kruger (2019)]. Teaching and experimentation of IoT while mentoring on cybersecurity risks have also been conducted to inspire inter-disciplinary solutions through technology leadership and innovation [Kruger (2018); Turpin, Matthee and Kruger (2020)].

By using document analysis and established literature guidelines, essential practices and associated outputs were investigated. This included sources through media outputs, academic engagements, and consultations with stakeholders of the environment. Table 1 below notes practices that facilitate rapid innovation established before the pandemic used to address the above findings.

Table 1. Identified practices and outputs

Practices that affect adoption	Support area outputs
Investigate new digital services	Support new business models
Provide access to novel I4.0 technologies	Facilitate an explorative mindset and ability to fail
	Facilitate safe interactions
	Support lifelong learning
Create projects that demonstrate 4IR technology	Rapid prototyping
	Interdisciplinary skills development
	Ideation
Aid in new methods of digitisation	Increased access to knowledge
Provide advisory services on technology applications and advancement	Support innovation and creativity
	Research and development (R & D)
Mentorship	Facilitate relevant skills development
Industry and community collaboration	Technology validation and testing relevant concepts
	Access to needed skills
	Create effective partnerships
	Commercialisation

Source: Adapted from [(Chong *et al.* (2018); Kruger and Steyn (2020); Manero *et al.* (2020); Sony and Naik (2020); Turpin *et al*. (2020); Walsh *et al*. (2017)].

4.2. *Community systems*

One of the above practices is collaborative engagements, predominantly within ecosystems of innovation. This is to form part of a larger community to share skills [George *et al.* (2020)]. Prior to the pandemic, there was a focus on academic partnerships as well as business [Rayna *et al*. (2015)]. However, the maker community is said to be a focal point. The systems used within these communities were developed for expertise to be shared, best practices brought, and open knowledge sharing. These efforts aided in each makerspace being more capable of addressing the unique contexts in which they operate, including the pandemic aligning with international efforts [Manero *et al*. (2020)]. As such, initiatives can be incorporated or channelled through such spaces, making them a key part of strategy as a CSF [(Sony & Naik (2020)].

4.3. *Addressing the pandemics problems through an innovative environment*

Manufacturers were struggling to address the demands for PPE. To address this, the Makerspace was a central space to develop solutions for the PPE shortages by channelling expertise and resources. One of the primary solutions was creating visor frames for facial shields for healthcare workers in the greater Tshwane metropolitan. The creation of these was done using open-source files provided by the international community and optimising them where required using Computer-Aided Design (CAD). AM technologies use a layering approach to create objects from CAD, and as a result, is slower than mass production techniques such as injection moulding [Manero *et al.* (2020)]. For this project, the challenge to create PPE quickly though was the focus point. To respond, several phases of implementation were noted, as reviewed in Fig. 4. Nevertheless, these lower-level technology solutions could be rapidly developed until such a time mass production occurred. This was because, despite the supply chain not being prepared as a whole, the innovation environment could capitalise on new production methods and innovation to rapidly shift production towards supply needs [Armani *et al*. (2020)]. From a CSF standpoint, the innovation environment aligned within existing literature by integrating smart technologies to create flexible and efficient production. Moreover, there was also effective project management to ensure effective implementation [(Sony & Naik (2020)].

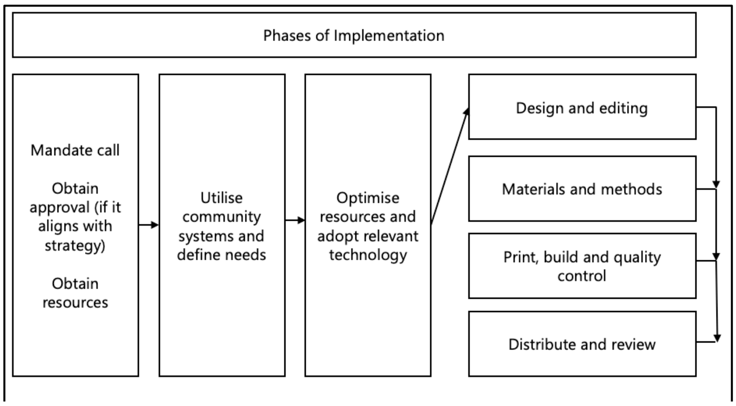

Fig. 4. Phases of implementation to address relevant problems such as PPE shortage.

4.4. ***Processes to address relevant needs***

The call for innovation went out in early April 2020, stating that help was required to produce PPE quickly and create sustainable solutions that could aid frontline workers in the pandemic. Before embarking on the call, approval and scope are vital aspects for consideration. This includes the specific environments prioritised, quantities that can be produced as well as associated resources required. Once approved, internal networks were leveraged to pool expertise, materials and access to the environment during the stringent lockdown, including updated operational procedures. The expert labour was noted, despite limited, and distribution would occur to local clinics as well as the universities health sciences faculty, who partnered with the metropolitan's academic hospital.

4.5. ***Design methods and editing***

When designing how to make objects, there are various techniques at the disposal of makers today. From physically built prototypes to Computer Numerical Control (CNC), machines produce material through subtraction. However, for this movement, 3D printing was selected as it was said to be well suited to the task, with minimal modification to switch between product creation as and when needs changed. AM technologies facilitate an inherently agile ability to change input files created through CAD, with the advantage that complex geometric structures can be designed and created instead of having individual parts manufactured. These defined characteristics are impacted by the material used, the pattern assigned and the infill density as specified in the G-code. As a result, fused filament fabrication (FFF) based on Fused Deposition Modelling (FDM), which is a category of AM was used [Steenhuis *et al.* (2020)]. FDM was used as it is quickly set up for manufacturing. In order to create objects, a file is required, which is created using CAD, and then converted primarily to G-code for a 3D printer to understand [Clifton, Damon and Martin (2020)]. G-code, also referred to as RS-274, has several variants and is a language used by people to inform computerised machine tools how to make something. The machines use these instructions to move the motors and assign paths for a set outcome. Due to the lower costing of such technologies and associated filament, the barriers to entry and support initiatives became more viable. For the actual design, there was a focus on open-source software and associated platforms to allow for the sharing of updated models [Chong *et al.* (2018)]. This made it possible for various stakeholders to create complex objects, even those with limited CAD skills. The primary designs used in the space are noted in Table 2. It also summarises some of the design aspects and linkages to the standard open source files. It is important to note that 3D print volumes do have an impact; however, if the objects are placed and altered on the build plate for each machine, print volumes, times, and materials differ.

Table 2. Review of devices open to editing and reproduction

Schedule	Capacity
NanoHack Protective Mask	Basic protection mask that is fitted directly to the face
PRUSA RC 1 Face shield	RC1 face shield. A partially circumferential headframe that has a clamp to hold a visor in place. Originates from Prusa Research, Holešovice, Czech Republic

PRUSA RC 2 Face shield	An updated face shield known as RC2. The headframe provides similar structural rigidity without the need for a clamp. Both units provide large surface protection.
Easy 3D Face shield	This is a face shield that does not require a clamp. Originate from Hanoch Hemmerich, La Laguna, Tenerife, Spain
Budmen V3, Face shield	Stiffened face shield holder with no clamps required. Budme Industries, Philadelphia, PA
H connector Ventilators	Expand usage of a single ventilator to ventilate up to four adults
Hands-free door opener	Attaches to handles to prevent contact

Source: Adapted from [Belhouideg (2020); Tarfaoui *et al.* (2020)].

4.6. *Materials and methods*

The primary material used to create this was Polylactic Acid (PLA) and Super PLA plastic. This plastic is non-toxic, versatile and affordable when compared to other materials. The filament made use of the FDM. Acrylonitrile butadiene styrene (ABS) was another option, but the focus remained on PLA as it required lower printing temperatures, ranging from 200ºC -225ºC, with less warping and extrusion issues. On the other hand, the ABS materials print at a higher range - 230ºC -255ºC – and generate toxic fumes while printing. Although other durable materials and thermoplastics such as Nylon are available, the need for higher speeds and lower costs channelled the widespread adoption of PLA [Armijo *et al.* (2020)]. Another reason is that a small amount of this material is used for support structures and rafts, which needs to be removed for post-processing. The raft is used for printers that struggle with adhesion as they do not have a heated bed, which can be seen in Fig. 5., with small layers being placed for easy adhesion of print material. Standard settings included using a 0.2mm layer thickness, extruding at 215ºC on a heated bed of 50ºC, which is standard for such renders [Oth *et al.* (2019)].

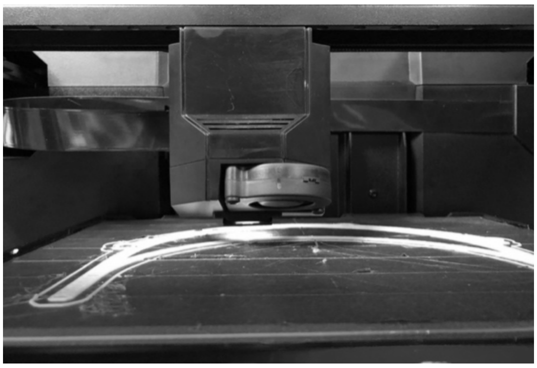

Fig. 5. Creating a raft for 3D printed headband adhesion.

Several 3D printers were used to create these visor frames, where the number produced depends on the capabilities of the machine. In some instances, only one print could be handled at a time. On others, they were configured to print multiple versions stacked upon one another. Overall, this allowed for an average production time of one visor frame per hour and was also attributable to printer configurations as well as modifications to the files available. During the initial phases, the machines were tested and pushed to the limits, and failures did occur. However, after several iterations, quicker and durable versions could be created. The material also facilitates that the centre's staff could optimise printer settings for each printer to ensure optimal results. The capacity at the time allowed for the production of around 20 units per day. As additional resources and optimisation took place, this increased accordingly. It is worth noting that the call for printing went out to anyone in the metropolitan region with a 3D printer. As part of collaborative efforts and ecosystems of innovation, the on-campus technology business incubator also aided in visor creation with their 3D printers. To distribute units, the collection was arranged with key stakeholders. For fewer than two months, over a thousand units were produced and distributed.

When factoring in methods and materials, limitations and dangers in using PPE were noted. With the potential for mechanical blockage of viral material, 3D printing materials have varying levels of specifications and reproducibility based on varying factors. This includes the material itself, the printers used and settings, and ambient temperature, moisture, lighting, and wind. The designed standard tessellation (STL) files provide a virtual model, but slight variances in G-code to optimise printing of thermoplastics did present a problem with exact replication. Despite these challenges, the aim was to provide needed equipment quickly until such a time that mass-produced products [Clifton *et al.* (2020)].

4.7. *Print, Build and Quality control*

Once design and materials were selected, the rendering to g-code for each machine needed to be completed. When rendering the CAD files, it must be noted that there can be limited adhesion, which causes failures and density variations when compared to subtractive methods such as CNC. The challenge was finding the most efficient means of production while minimising risk and optimising resource usage. The goal was to create parameters that optimised printing while considering the time sensitivity. Therefore, printing settings alterations allowed for optimised throughput and was achieved with specific configurations as well as print times set to time the most optimal methods. These were then rendered for production. The unit's components can be seen in Fig. 6., with a completed version shown alongside it. With the adhesion methods, though, several issues were experienced, which caused failed prints, excessive stringing and lowered quality. In the latter cases, this impacted postproduction processes.

Fig. 6. Completed prints with final product.

The building of shields was done with the help of available staff, following a production like process of cutting Perspex and elastic string before assembling everything together. Disinfection played a key role, and stakeholders from the medical faculty were directly inclined to identify the possible treatments, including chemical treatment, chemical vapour, or irradiation. For the context of SA, the chemical bath appeared most viable. This was done after the shields were completed and before distribution to workers. In terms of sterilisation of the plastic, it is considered sterile as it leaves the extruder between 210°C - 220°C. This surpasses the required 121°C. However, contamination of the airflow in the environment, build plate and packaging remains present. The use of conventional sterilisation of the object as well as packaging was used. For PLA, a common biomaterial would melt if the 5-minute sterilisation cycle is used with steam. This also depends on the form of polymer used in terms of PLA, which is composed of L-lactide and D-lactide chains. The specific properties relating to PLA, such as thermal and mechanical, depend on the distribution ratio of these chains. Thus, the melting temperatures could vary from one brand to another, especially when factoring in Super PLA [Oth *et al*. (2019)]. It is interesting to note that thermal sterilisation across the European Union is prohibited in hospitals at the time of writing. A reason presented was the inactivity of prions. Although other forms of sterilisation such as radiation and ethylene oxide are used in other areas such as food, these could not be used in this instance as they can potentially create toxicity on the surface of these objects. As a result, a safer technique is the low-temperature sterilisation with hydrogen peroxide as residues are not formed [Oth *et al*. (2019)].

4.8. *Distribution and review*

At the time of writing, manufacturers were able to create these visors on a massive scale. However, further services have been expanded within the makerspace to produce other PPE for other departments. Examples include social distancing flags, door opening mechanisms and investigations into potential models for further PPE needs. External organisations were manufacturing ventilator parts. In the meantime, further mandates such as ear savers were requested.

5. Discussion

This study expanded on how I4.0 technology such as AM was used during the pandemic [Singh *et al.* (2020)] and the role of an innovation environment. It was found that the pandemic accelerated the need for innovation in several areas including the need to produce PPE. The case study showed that a makerspace can be an innovation environment under certain conditions, where the process to create needed PPE was shown. Several practices that align with needed CSF were identified that supported early-stage adoption of AM to achieve this even in a developing country context [Armani *et al.* (2020); Choong *et al.* (2020)]. Furthermore, it was shown that there is need to maintain and support innovation through technology adoption [Coronado-Medina *et al.* (2020); Das (2020)], where this is an expansion on a mechanism to achieve this [George *et al.* (2020)] including that of SA [Ayentimi and Burgess, (2019)].

With the activities and documents reviewed, the makerspace assessed showed a strong association with innovation by creating conducive facilitating conductions of the UTUAT model. A reason for this could be the practices identified in Table 1 that are applied in various scopes and disciplines, where some of which align with CSF [Pozzi *et al.* (2021)]. The makerspace as an innovation environment was shown to also support facilitating conditions by sharing infrastructure and pooling resources distributed over geographical locations towards rapid and targeted efforts [Sharma (2021)]. This includes the effective adoption AM advancing its maturity within the academic space [Hajoary (2021)]. Moreover, due to the capabilities of such an environment, there are some key similarities with DIHs that could account for the innovation development, such as the channelling of expertise and partnership development, demonstrating that core services of DIHs can be applied within developing regions as well [Crupi *et al.* (2020)].

From this space, as with similar studies, the usefulness of AM was shown as an agile production technology that can be adapted to address various situations and associated needs [Armani *et al.* (2020); Chong *et al.* (2018); Corsini *et al.* (2021); Manero *et al.* (2020)]. AM perceived usefulness can be said to have been enhanced due to the support of a larger innovation ecosystem, as key designs to create several components eased PEoU [Verma and Prakash (2021)]. Furthermore, it was found that AM as a technology adoption paradigm was increased rapidly due to the pandemic, not only for PPE but also other facets in rapidly prototyping solutions within the 4IR [Schumacher *et al.* (2016)]. It was also shown how such technology integrates into larger ecosystems with the support of innovation environments to enable rapid strategic responses [Lu (2017)]. It is worthwhile to note that, after time, these efforts would later be replaced by injection moulding, which is a production process significantly more efficient than AM. This is noted as one of the barriers of AM, where much more robust production outputs are required, especially for medical equipment [François *et al.* (2020)].

Theoretically, various constructs impact technology adoption, including societies perceptions of technological capabilities [Singh *et al.* (2020)]. In this case there was rapid dissemination of prototypes as a key deliverable, further proving a case for AM. However, several risks and considerations are present. This includes reproducible methods [Clifton *et al.* (2020)] and integration within existing systems [Tino *et al.* (2020)] which places innovation environments as key pillars to support established CSF for I4.0 technology adoption. However, further research is required to address other aspects and application of models such as TAM and UTAUT when considering these new technologies' rapid pace and impact [Masood and Sonntag (2020)]. Further theoretical considerations include the following:

- Many studies consider the nature and adoption of technology, although what constitutes a novel, disruptive, state of the art, smart or high technology is unclear and warrants further investigation.
- Usefulness perceptions can change due to accelerated needs, as with those faced with the context of the pandemic. This should be noted when adopting theory and the potential risks when pushing new technology adoptions.
- Low levels of trust can hinder new incumbents entering innovation ecosystems, limiting the usage of novel technologies.
- Constant feedback loops and communication between the different users such as designers, procurement of raw materials, supply chain managers and engineers are key variables that could be expanded under the UTAUT model that impacts perceptions. As such, collaboration needs to be factored into analysis points and noted as a CSF.

From a practical point, innovation environments have been shown to facilitate improvements for academia by channelling needed resources and leveraging technology. This paper adds that newer novel technologies in conjunction with key theoretical principles can address real-world problems. The constructs of theory such as user perception are vital, and innovation environments could potentially aid in this regard. However, due to the limited nature of the studies focus, generalisation is not possible. Nevertheless, a few thoughts are present from a practical standpoint.

Innovation environments can form a key part of infrastructure towards innovation. Having the capacity to access such environments can allow users (or employees) to evaluate and test parts, capacities and technologies. They could also alleviate supply chain disruptions in the short term, such as those caused by the pandemic [Luthra *et al*. (2020)]. If in place they can be used as central points in leveraging existing communities of practice and support true collaboration to enhance innovation capacity. This means they can act as key areas to positively impact facilitating conditions that affects technology adoption [Venkatesh *et al*. (2003)]. Moreover, there can be a drive to develop digital hubs such as the DIHs at a country wide level to support needed skills development. Skills are considered a CSF to effectively adopt I4.0 technologies for large organisations but also SMEs [Crupi *et al*. (2020)] to grasp opportunities of this paradigm [Moeuf *et al*. (2020)].

However, failure rates of accelerators and incubators within both business and academic constructs cannot be overlooked. This is one example where an innovation mechanism has continually delivered, but this relies on well-skilled task forces. Finally, the inequity between communities can be disproportional without access to such infrastructure, leading to skewed technology adoption rates [Sharma (2021)].

Universities can broaden technology adoption through innovation environments. Universities are often considered drivers and developers of the knowledge economy. As a result, they are looked to as sources of innovation [Chang (2017)]. This has been shown through successful initiatives such as the commercialisation of research through various aspects [Cunningham *et al*. (2019); Kruger and Steyn (2019)]. By facilitating this through an innovation environment such as a makerspace, faculties can broaden technology adoption to develop further innovations in research and generate viable commercial outcomes. This case showed an innovative approach towards tools and equipment for hospitals, such as surgical equipment of use-specific tools. This demonstrates an innovation environment's role to enable CSF towards smart technology integration [de Sousa Jabbour *et al*. (2018)].

Managing advancing technologies such as AM. AM as a technology of I4.0 can adapt to change and react to needs to enable agility in various fields [Schumacher *et al.* (2016)]. The usefulness of these technologies in a developing country can be promoted and aid in supporting innovation with project management as a CSF [de Sousa Jabbour *et al*. (2018)]. There are, however, limitations and challenges with AM. Raw materials usages and recycling need to be considered as well as quality control management. This requires maintenance of machines and key knowledge in their usages such as bed adhesion, temperature, warping of plastics due to ambient temperatures, clearing of blocked nozzles, lubrication of moving parts, broken fans and upgrading of firmware [Steenhuis & Pretorius (2017)]. In addition, several issues can occur during printing requiring constant monitoring if the settings are not optimised with these variables.

Going forward, actors on all fronts need to effectively manage changes and navigate novel technologies based on practical constructs of theory such as PEoU, owners' characteristics and the owners' consent. The main contribution, based on the findings and existing literature, is a design model to guide developing countries to strengthen innovation capabilities with novel technologies of I4.0 [Asplund *et al*. (2021)]. The model is shown in Fig. 6. In these activities, though, reckless developments and oversight of ethics remain a concern despite the novelties and capabilities brought on by the 4IR. When rendering and designing then, terms and conditions of open source content should be considered, especially where the purpose would be towards profiteering [Tarfaoui *et al*. (2020)]. This adds to the literature by showing how state of the art technologies can be channelled through such environments, strengthening innovation ecosystems in even developing regions, to achieve several of the benefits of the 4IR paradigm [Xu *et al*. (2018)].

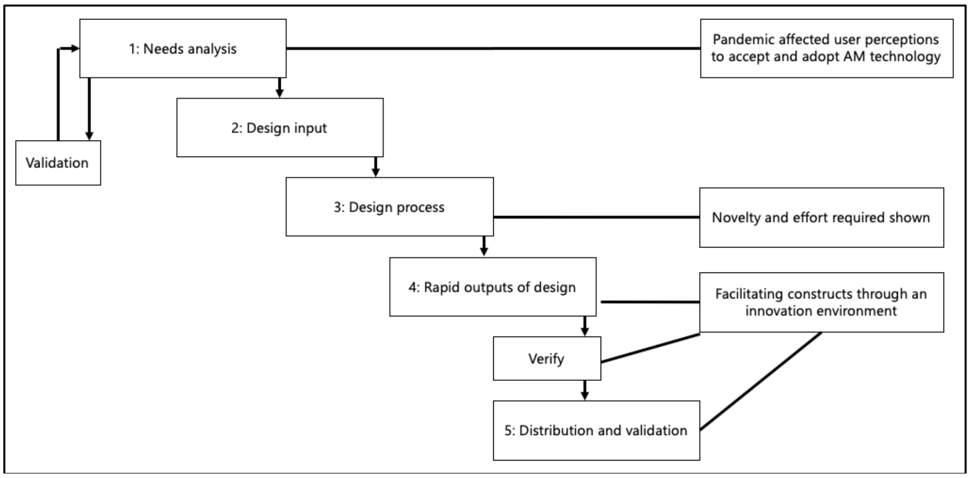

Fig. 6. Design model to adopt and apply innovative technology.

6. Conclusion

Large-scale adoption of technology in the present context was shown to enable innovation across economies to address challenges of the COVID-19 pandemic. This was achieved through a global community movement that leveraged rapid advances in I4.0 technology, specifically AM, towards the next generation of manufacturing. Part of which was a makerspace, which from the findings was shown to be an innovation environment given certain parameters. Furthermore, certain practices that support adoption were identified, which included the usage of community systems. By using these principles, it was shown how this central space was able to develop PPE and address supply chain shortages by channelling expertise and resources. In this sense the case demonstrated how early-stage adoption could be channelled quickly through such an environment to streamline adoption even in a developing country. The adoption of this depends on certain constructs as specified in the TAM and UTUAT model, which were shown to have applications in the field of I4.0 and by extension, the 4IR.

Based on these findings a model was developed and presented to provide a starting point for using innovation environments as infrastructure to support innovation by driving technology adoption for rapid and targeted solutions development.

Limitations and suggestions for future research

This study, although striving for academic rigour has several limitations. First and foremost is that the study took place in a narrowly defined area. Due to this context the study provides limited insights and generalisation of the model.

Based on this, it would be interesting to see how other developing countries used AM and other I4.0 technologies, but more importantly, where they originated. For example, did they originate within academic environments, R&D labs or business spin-offs that are associated with being agile in technology adoption.

The model and analysis assumed that the constructs of the TAM and UTUAT models, especially facilitating conditions is applicable to I4.0. It would be interesting to note what other models are used and compare their usefulness and effectiveness in current studies.

It was noted that by reverse engineering solutions, medical testing of the equipment's effectiveness and standardisation raises several concerns. As a result, regulation presents a significant gap for future research in that standardisation, testing and intellectual property are vague when using novel technologies such as AM which can replicate existing products.

Finally, the specific skills contained with not only this makerspace, but other similar environments that can enhance technology were not specially noted; although they do play important role. The skill set required then in this regard requires future investigation.

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